EML 4905 Senior Design Project

A B.S. THESIS
PREPARED IN PARTIAL FULFILLMENT OF THE
REQUIREMENT FOR THE DEGREE OF
BACHELOR OF SCIENCE
IN
MECHANICAL ENGINEERING

TORSIONAL SPLIT HOPKINSON BAR OPTIMIZATION

A Project in Conjunction with the Air Force Research Lab

Lorraine Fuentes
Jonathan Gomez-Leon
Camilo Trujillo

Advisor: Professor Dr. Sabri Tosunoglu

April 10, 2012

This report is written in partial fulfillment of the requirements in EML 4511. The contents represent the opinion of the authors and not the Department of Mechanical and Materials Engineering.

Report Documentation Page	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE **10 APR 2012**	2. REPORT TYPE	3. DATES COVERED **00-00-2012 to 00-00-2012**

4. TITLE AND SUBTITLE **Torsional Split Hopkinson Bar Optimization**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Florida International University,Miami,FL,33199**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

The Torsional Split Hopkinson Bar is a piece of equipment used to perform testing of materials in order to measure mechanical properties by generating high strain rate shear stress-strain data. It works by propagating a torsional wave through an incident bar, reaching a specimen, and making the wave load the specimen. Once the specimen is loaded, the wave is partially reflected back and is partially transmitted through the transmitter bar. This simplified version of the process has as its objective to determine the load and deformation history of the specimen to obtain various mechanical properties of the material such as shear stress and strain.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**108**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Ethics Statement and Signatures

The work submitted in this B.S. thesis is solely prepared by a team consisting of Lorraine Fuentes, Jonathan Gomez-Leon, and Camilo Trujillo and it is original. Excerpts from others' work have been clearly identified, their work acknowledged within the text and listed in the list of references. All of the engineering drawings, computer programs, formulations, design work, prototype development and testing reported in this document are also original and prepared by the same team of students.

Lorraine Fuentes	Jonathan Gomez-Leon	Camilo Trujillo
Team Member	Team Member	Team Member

Dr. Sabri Tosunoglu	Dr. Joel House
Faculty Advisor	AFRL Advisor

Table of Contents

List of Tables

List of Figures

Abstract

The Air Force Research Lab faced some challenges regarding their Torsional Split Hopkinson (Kolsky) Bar. This apparatus is used to measure various mechanical properties of materials such as shear stress and strain at high strain rates. The results obtained using the torsional Kolsky bar allow for the improvement and development of military equipment such as armor, weaponry, and military transportation such as tanks and aircraft. The issues with the Air Force Research Lab's bar manifest in experimental testing results yielding anomalies in the stress-strain diagrams due to lack of parabolic increase. These faulty results are due to movement of the specimen/bar interface during the propagation of the torsional wave.

The purpose of this project is to work in conjunction with the Air Force Research Lab to conceptualize and ultimately resolve the problems encountered with the Torsional Split Hopkinson Bar (TSHB). This is accomplished by eliminating the relative motion between the specimen and the bar by redesigning the specimen placing area in order for the wave to propagate generating correct results.

Introduction

The Torsional Split Hopkinson Bar is a piece of equipment used to perform testing of materials in order to measure mechanical properties by generating high strain rate shear stress-strain data. It works by propagating a torsional wave through an incident bar, reaching a specimen, and making the wave load the specimen. Once the specimen is loaded, the wave is partially reflected back and is partially transmitted through the transmitter bar. This simplified version of the process has as its objective to determine the load and deformation history of the specimen to obtain various mechanical properties of the material such as shear stress and strain.

Problem Statement

The problems that arise with the Air Force Research Lab's (AFRL) torsional Kolsky bar are concentrated in the area where the specimen is located. Currently, the setscrews that hold the specimen in place with the incident and transmitter bars do not have enough tension; therefore relative motion in the specimen/bar interface is present. This circumstance is why anomalies are present in the data. The torsional wave that propagates through the apparatus experiences an irregularity when reaching the specimen. The relative motion that is generated between the specimen and the bar causes the torsional wave to propagate in a non-uniform way. This kind of propagation produces inaccurate readings in the gages.


Figure 1 Current Bar/Specimen Interface Configuration [8]

Ideally, the grip region of the sample and the bars do not experience any motion of one relative to the other during an experiment. This implies that the torsional wave propagates in a uniform way and the stress-strain diagram does not display perceptible jumps.

A comparison is done between data acquired during stress-strain tests by the AFRL and NSWC. The stress-strain graphs are obtained from tests done to an aluminum specimen provided by NSWC. It can be seen from Figure 2 that anomaly is present in the diagram whereas Figure 3 does not present any. The root of the problem is the relative motion between the specimen and the bars, creating faulty readings.

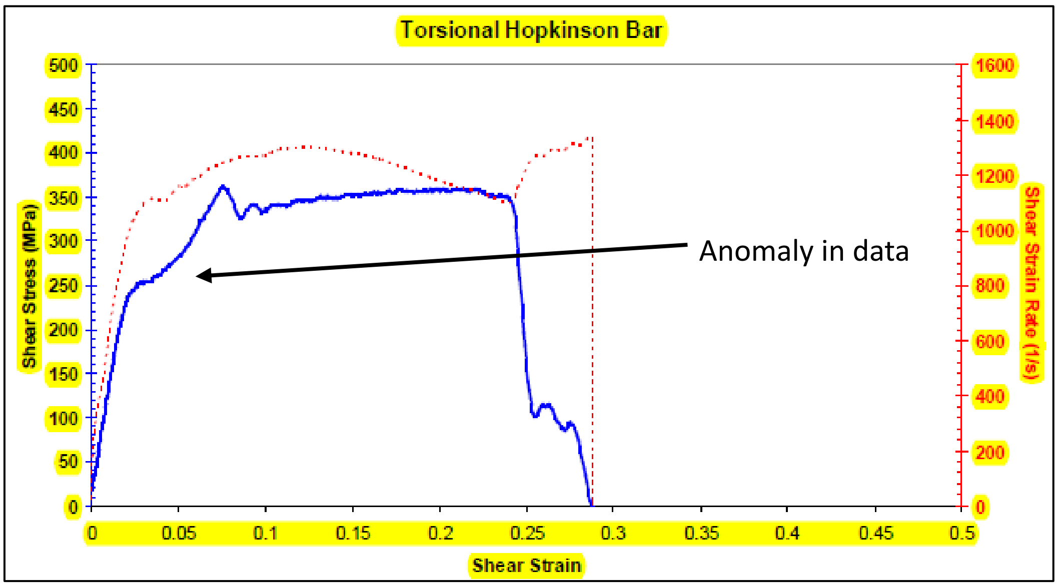


Figure 2 Stress-Strain Diagram from Eglin Base

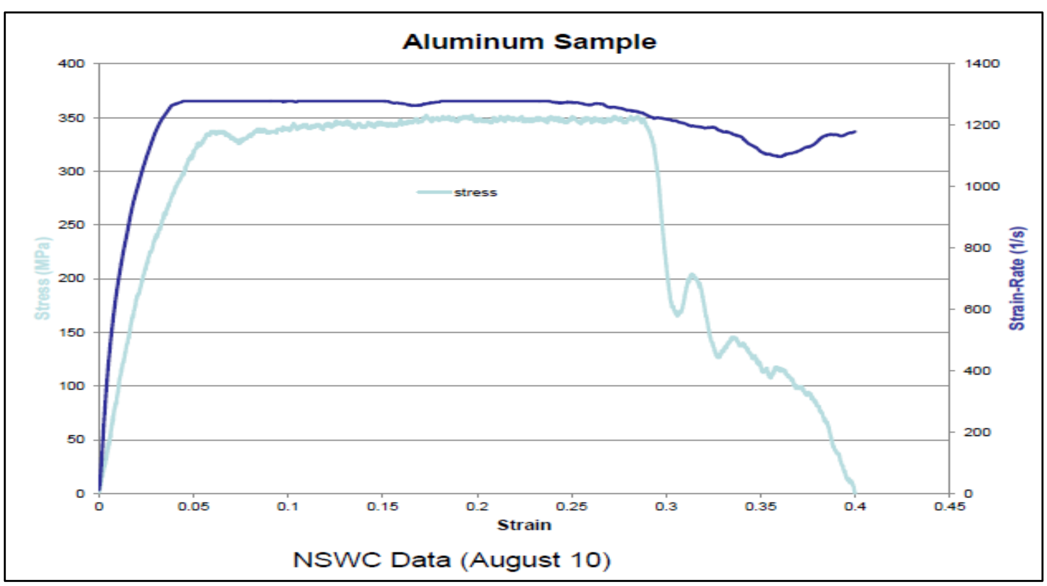


Figure 3 Stress-Strain Diagram by NSWC

Motivation

The United States Air Force is constantly conducting research on applications and development of new ordnance and aerospace equipment. These researches are used to improve National Security and support Military operations in order for United States soldiers to have a better defense and security.

An important aspect of every component that is used in the military is the material. For example, an aircraft must be designed so that it can endure different environments and situations, creating the need to use strong, yet light materials in order to be more efficient. From the same token is the design of missiles with specifications that are crucial for the optimum operation of the product. Both of these examples require material testing to comply with the necessary stipulations.

Anything from ordnance to an aircraft can benefit greatly from material testing. By measuring the mechanical properties of materials, the United States Air Force can improve the performance of much of its equipment.

Figure 4 US Air Force Delta II Rocket [7]

Examples of the military applications that benefit from testing with the torsional Kolsky bar can be seen in Figures 4 and 5.

Figure 5 Air Force Massive Ordnance Air Blast Bomb [6]

Literature Survey

One of the first instances regarding the use of a technique for testing material properties with the use of a bar took place in 1949 when Kolsky created the split-Hopkinson bar [1]. This device consisted of placing a specimen between two cylindrical bars and propagating a pulse through it. This experiment allowed the measurement of displacement and loads that affected the specimen. From this, Kolsky proved that the specimen displayed axial stress due to the wave propagating through it, and that the magnitude of the wave that is reflected back is proportional to its strain rate [1]. With the elastic stress waves in the incident and transmitter bars, Kolsky determined the stress-strain response of the specimen [2]. These scientific advancements demonstrated the benefits of using this type of experiment to measure mechanical properties of materials. Due to this, in 1966, Baker and Yew developed a torsional Kolsky bar with which the shear stress and strain were measured and the torsional wave was created through the release of a pre-twisted clamped section of an elastic bar [1].

There are two different designs of clamps to be used in the torsional Kolsky bar. Both designs are hydraulic and operate in the same manner.

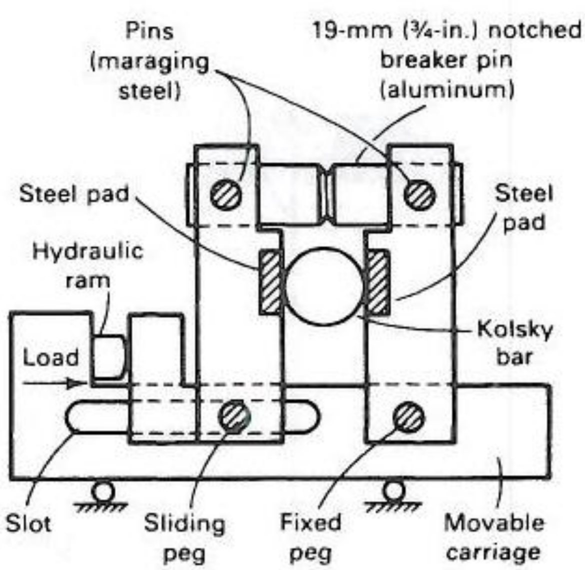


Figure 6 Clamp Designed by J. Duffy [1]

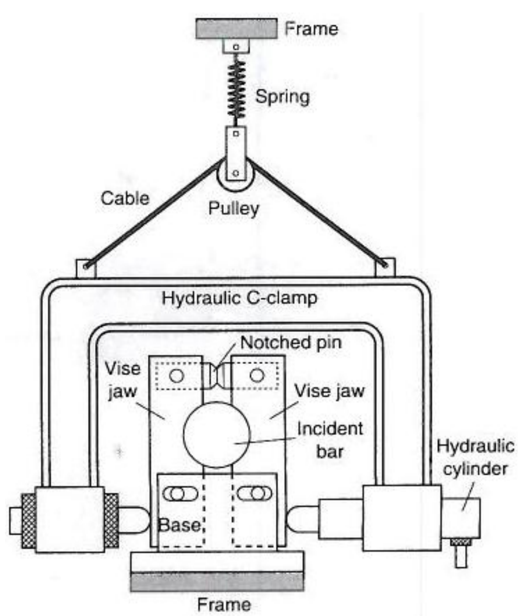


Figure 7 Clamp Designed by Gilat [1]

The clamp used by the Air Force Research Lab is shown in Figure 7 designed by J.-Duffy. The main difference between these two bars is that the design that uses the C-clamp is self-adjusting to the location of the bar and arms of the clamp and can easily adapt to whatever diameter the bars have.

In addition, there are two different methods for generating the torsional wave through the incident bar. One is the stored torque technique, which is the technique that the Air Force Research Lab employs with their torsional Kolsky bar and is thoroughly described in this document. The alternate technique is performed by means of explosive loading to generate the torsional wave by simultaneously detonating two explosives. An advantage to using this technique is that the torsion pulse rise time is as much as three times lower than the pulse rise time in the stored torque technique. On the other hand, the amplitude of the created torsional pulse is not constant; therefore the specimen would be loaded at a time-varying strain rate.

Description

The torsional Kolsky bar belonging to the AFRL is composed of the specimen, two collinear bars, the incident and transmitter bars respectively, the torque cam, the clamp and notched breaker pin, various bearings, and strain gauges.

Specimen

The specimen is located between the two collinear bars and receives and partially reflects the torsional wave, responsible for loading the specimen in shear at high rate. The sample is most frequently made of materials such as metals, ceramics, or polymers. The gage section of the specimen is a thin walled tube [2]. It is placed between hexagonal flanges with matching sockets in order to provide for strong mechanical connections. This allows for the prevention of relative motion in the specimen/bar interface. Additionally, the specimen is held in place by being inserted into hex pockets located in both bars and attached by set screws on both of its ends. As can be seen, the current geometry and configuration were carefully selected to avoid loss of motion between the specimen and the bars as the shear stress pulse passes [1]. However, this has not yet been successful.

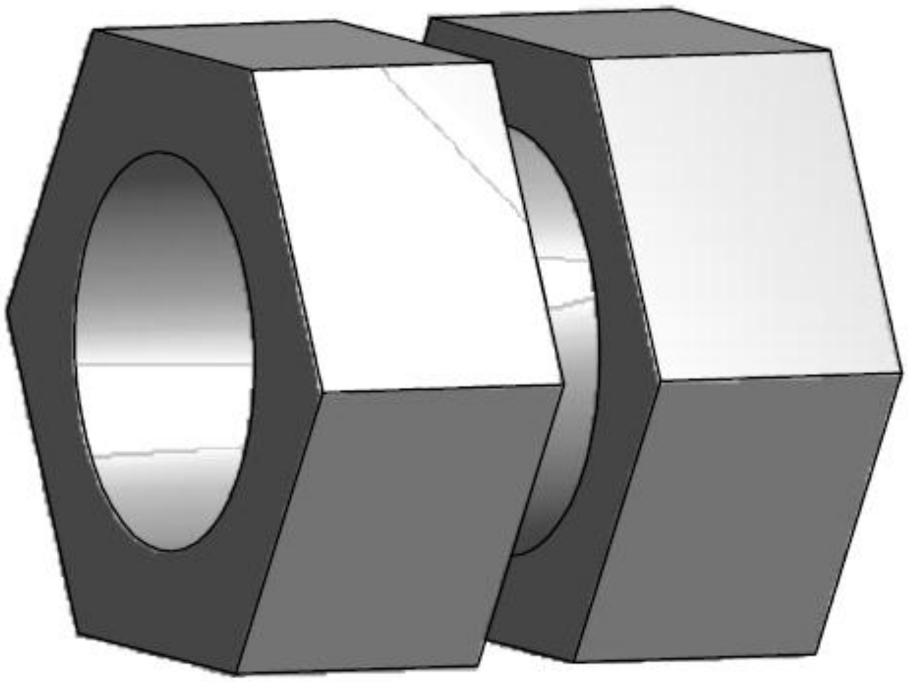


Figure 8 Torsional Kolsky Bar Test Specimen [5]

The Bars

Two bars compose the TSHB assembly. These are the incident and the transmitter bars. The first is responsible for generating and propagating the torsional wave that reaches the specimen. When this occurs, the wave loads the specimen and is partially reflected back to the incident bar and partially transmitted to the transmitter bar, the second bar. Material composition may vary but the AFRL's bars are made of aluminum. They are set in place by bearings that are locked in a position that keeps the bars aligned, allowing them to rotate freely. Both bars contain at their ends a hexagonal slot (hex pocket) in which the specimen is attached [2].

Torque Wheel and Clamp

This section of the bar is concerned with the initiation of the torsional wave that takes place by the sudden release of stored torque [1]. This occurs by first generating the torque with the torque wheel by twisting the incident bar with the use of a hydraulic hand pump and a cylinder. Secondly, this torque is stored with the use of the clamp which holds the bar from rotating. The clamp is placed together with a notched breaker pin, responsible for keeping the clamp tightened, preventing motion from the twisted input bar. The pin breaks when too much pumping hydraulic oil to the cylinder takes place [2]. This causes the release of the stored torque so that a shear stress pulse can propagate through the bar.

Conceptual Designs

The following designs constitute initial ideas towards eliminating the motion present in the specimen/bar interface when the shear stress pulse is propagated. These options involve redesigning the section of the bar in which the specimen is placed.

Six Jaw Chuck

The chuck falls in the category of clamps, which have different variations. They are used to hold objects that usually have some sort of rotation along its axis. Since the object that is being held is a hexagonal cylinder with radial symmetry, the chuck that is being described is self-centering with six jaws, corresponding to one jaw per face of the specimen.

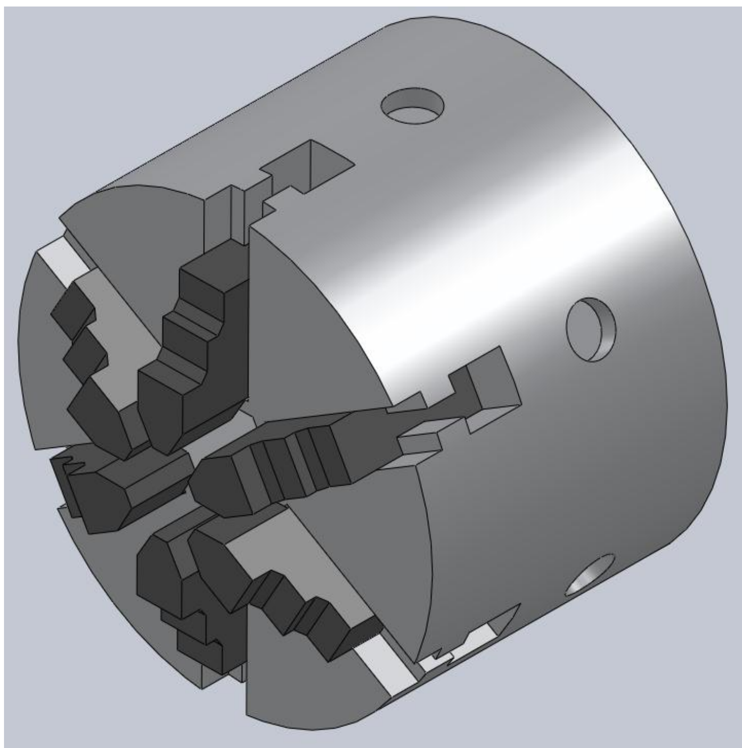


Figure 9 Conceptual Six Jaw Chuck - Isometric View

The six-jaw chuck as shown in Figure 9 is to be implemented in both the incident and transmitter bars. One option is welding or cementing the chuck to the bars. Alternatively, the bars on the Torsional Split Hopkinson bar can also be remanufactured in order for the chuck and the bars to be a one-piece component.

In the same manner, there are different possibilities on how the chuck can be driven, these usually work by mechanical means, using a screw to tighten or loosen the jaws. A pneumatic or hydraulic component can also be considered as means to drive the chuck to prevent motion of the specimen.

Figures 10 and 11 show the six-jaw chuck in a top and side view.

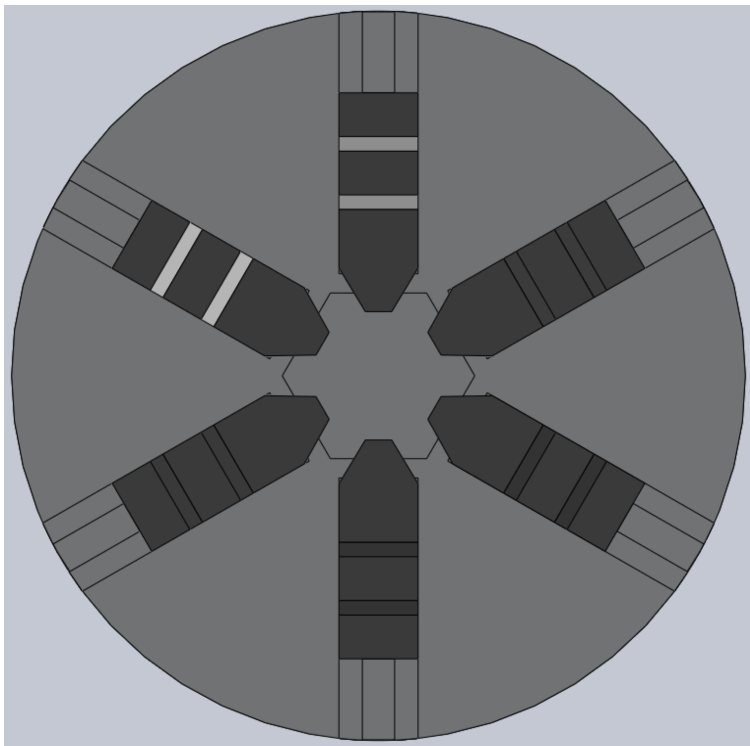


Figure 10 Conceptual Six Jaw Chuck - Top View

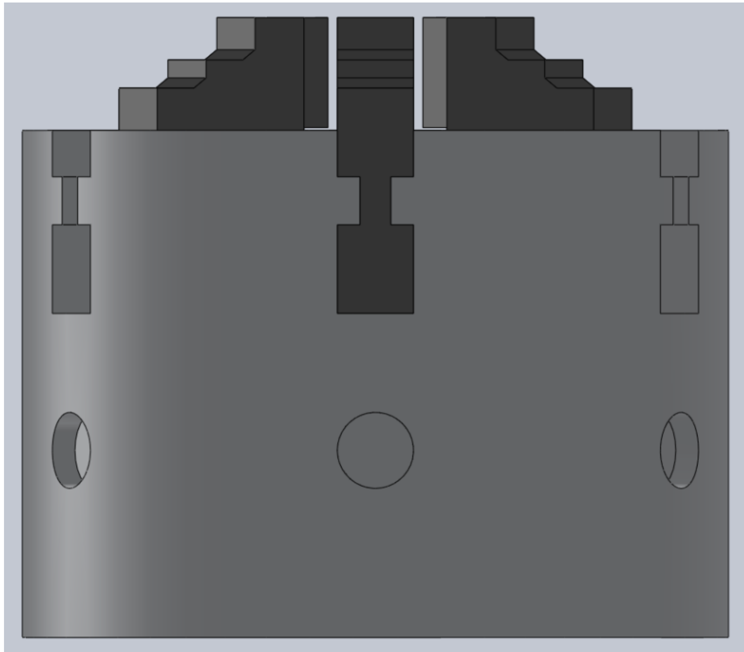


Figure 11 Conceptual Six Jaw Chuck - Side View

A collet, which follows the same concept as the six jaw chuck was contemplated, but initial analysis proved it was not going to work. This is because it tugs and pulls the faces of the specimen, creating an actual load, which would give faulty results.

Specimen Vise Holder

A vise is a mechanical apparatus developed to hold pieces down while work is performed on them. There are several configurations for vises, but the most common one is the bench vise. The way vises work is by having one of the jaws fixed and a parallel one moving towards or away from the fixed jaw by a screw. Given that the geometrical figure is in a hexagonal shape, the jaws of the vise are modified to grip each surface of the hexagonal specimen, as is shown in Figures 12 and 13.

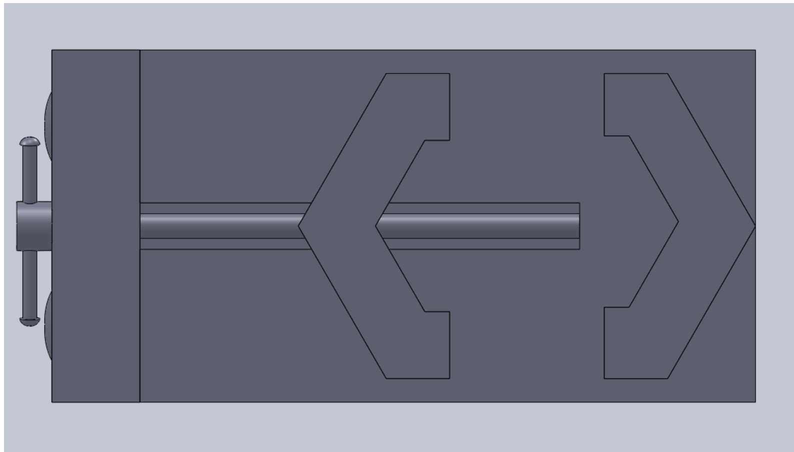


Figure 12 Conceptual Hexagonal Vise – Top view

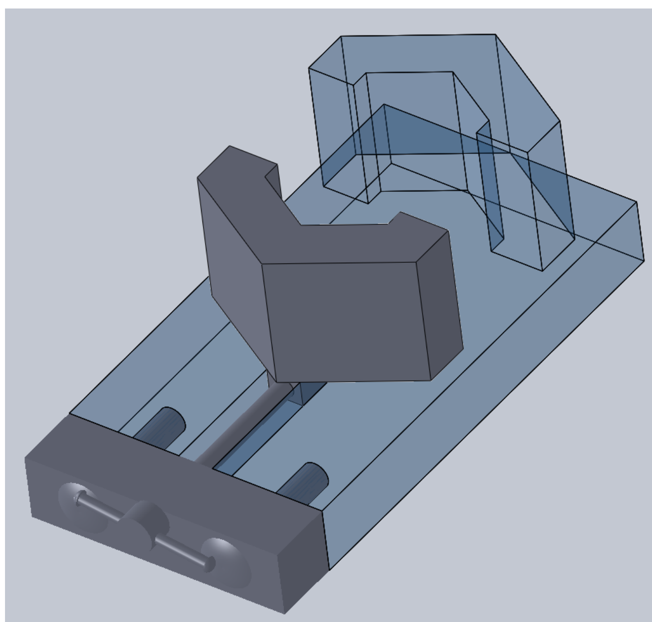


Figure 13 Conceptual Hexagonal Vise – Isometric View

The scheme is to either have the hexagonal vise welded to both the incident and the transmittance bars or to remanufacture the bars to include the hexagonal vise. Remanufacturing would reduce the amount of moving parts due to welding.

Proposed Design

Detailed analysis of the designs that can be implemented in the Torsional Split Hopkinson bar allowed for the development of a new design, resulting in the configuration depicted in Figure 14. The purpose of incorporating this proposed solution into the torsional Kolsky bar is so the bar/specimen interface does not experience relative motion during tests.

The design of the functional prototype is similar to the original equipment that is used by the Air Force Research Lab. In order to eliminate possible discrepancies in the data acquisition, the prototype is scaled down with enough space between the pillow blocks to place strain gages in each bar.

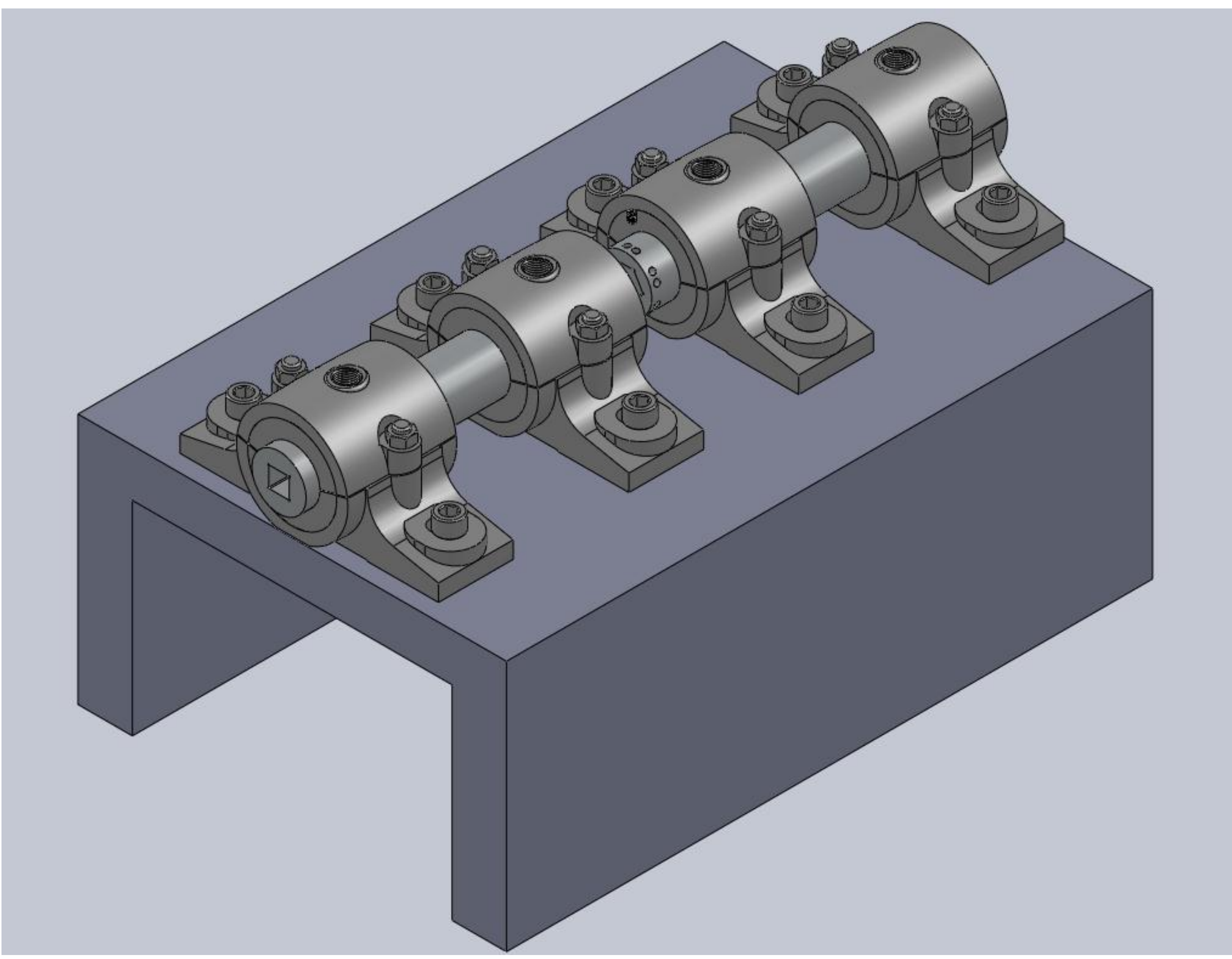


Figure 14 Proposed Design

The scale for the prototype is 1/16 of the original architecture. It is essential for the prototype to be as small as possible to have accurate results in the tests making the analysis reliable. At the same time, having a smaller prototype permits performing multiple tests on different bar configurations.

An important aspect of the prototype is that the tests are going to be conducted in a static environment as opposed to the original architecture of the bar, which performs dynamic tests. What this means from an operation standpoint is that, for static tests, the far end of the transmitter bar is fixed while the incident bar slowly rotates [13].

Additionally, both the incident and transmitter bars will have different configurations regarding the placement of the set screws. The AFRL's configuration has six set screws per bar that support the hexagonal specimen (one screw on each face). The desired configuration consists of each bar having 12 set screws. At the same time, a middle ground between 6 and 12 set screws is tested and analyzed to compare the variations. Detailed drawings of the 6 set screws and the 12 set screws configurations are presented in Appendix A.

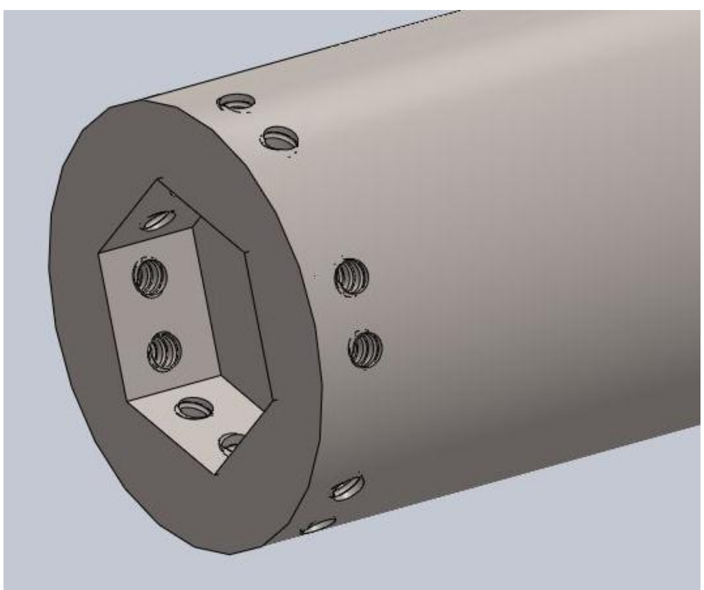


Figure 15 Design of 12 Set Screws - Isometric View

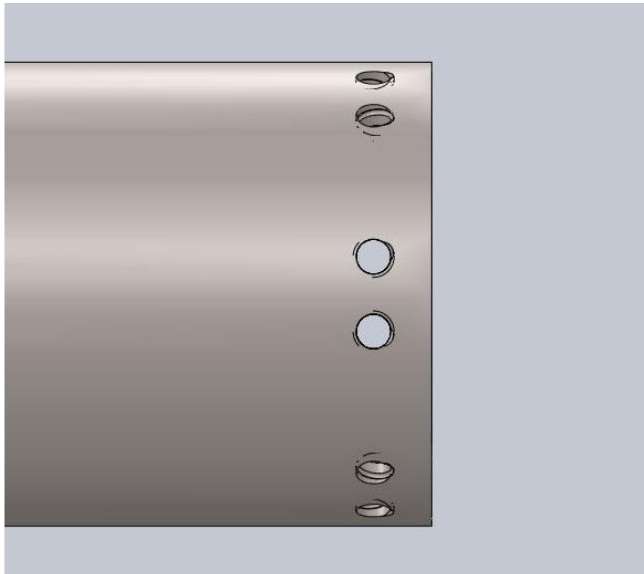


Figure 16 Design of 12 Set Screws - Side View

As can be seen in Figure 15, the design of the specimen/bar interface is similar to the current configuration used by the AFRL. The main difference with this proposed concept is that two set screws restrain each of the six faces of the hexagonal shaped specimen, whereas the current design contains only one set screw per face of the specimen. The addition of an extra set screw per face will contribute to eliminate the relative motion that exists when the stress pulse propagates through the bar. This modification is to be implemented in both the incident and transmitter bars.

There are several factors that contribute to the selection of the design in Figure 15 rather than the conceptual designs from the previous section. The six jaw chuck configuration contains many internal components and moving pieces and may result complicated to manufacture since the diameter of both the incident and transmitter bars is equal to 1 inch. In addition, all these moving pieces may be contributing to the problem rather than solving it. Evaluation shows that there may even be relative motion between the bar and specimen, causing the torsional wave not to propagate fully, dissipating some of its energy along the way. Similarly, the hexagonal vise presents similar issues; the torsional wave will not reach the specimen in its full capacity because of the different moving pieces involved with its configuration. Furthermore, significant modification must be made to the bars in order to incorporate any of the conceptual designs into the apparatus and this may worsen the problem.

Project Management

Timeline for Senior Design Project

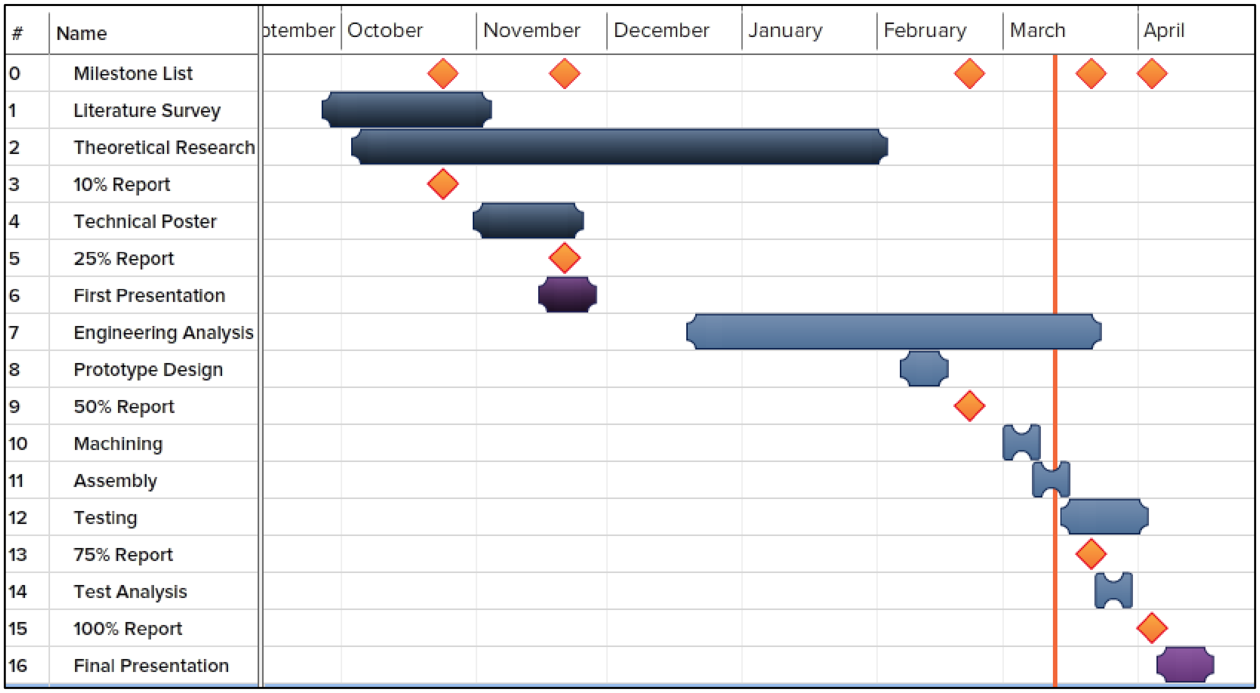


Figure 17 Project Gantt Chart

The Gantt chart in Figure 17 serves as an organizational tool to set dates and durations for the different tasks involved in the Senior Design Project. The report submissions as well as presentations for each semester are included since they represent important milestones in the project. The beginning of the project is marked by research and literature survey. As time progresses, the tasks become more engineering oriented and involve structural analysis as well as prototype planning. In order to comply with the objectives for the design, development, and testing of the prototype all the steps necessary are set in the chart and assigned a starting and ending date. This permits for prioritizing of goals and aids in meeting deadlines.

The distribution of responsibilities results in working with the strengths of each team member in order to efficiently achieve tasks and milestones. Lorraine Fuentes was the predominant liaison with the AFRL while Camilo Trujillo worked with purchase orders and manufacturers and the Jonathan Gomez-Leon interacted with the machining department. Regarding project responsibilities, all members performed research; however each team member specialized in a specific task such as the report, the design, and the simulation and engineering analysis.

Commercialization of the final product is not a goal for this project since the work performed during the time period outlined in Figure 17 is for an entity of high National security that does not consider sharing their test designs. As a matter of fact, the designs and models developed belong to the AFRL and will be used at their discretion for materials testing.

Engineering Analysis

The Torsional Split Hopkinson bar, as an apparatus for testing materials, requires certain analysis in order to better understand the experimental results and obtain the necessary values regarding shear stress and strain. As with any stress problem, there are three considerations that must be taken into account, geometry, boundary conditions or loading, and material response. These considerations form part of the analysis required with the torsional Kolsky bar since they characterize the end results. Each variation in any causes alterations, especially because they are interrelated. The following analysis established how stress, strain, and strain rate are calculated, as well as how the entire process behind the bar yields results regarding mechanical properties of materials. Also, relative motion is further explained to better understand this phenomenon.

Relationships with the Bars

The torsional wave that is propagated through the bar is characterized by a series of relationships. For instance, an elastic wave experiences a relationship between the torque, *T* and the angular velocity $\dot{\theta}$, denoted in equation 1.

$$\dot{\theta} = \frac{T}{\rho c J} \qquad \text{Equation 1}$$

Where ρ is the density, *J* is the polar moment of inertia, and *c* is the torsional wave speed. Also, one can relate the torque with the yield stress of the material, as seen in equation 2; where r is the radius of the bar.

$$T = \frac{\tau_y J}{r} \qquad \text{Equation 2}$$

A third equation is generated by introducing the shear modulus of elasticity, *G* since $c = \sqrt{(G / \rho)}$. This is done by substituting the torque into the second equation.

$$\dot{\theta} = \frac{\tau_y}{r\sqrt{\rho G}} \qquad \text{Equation 3}$$

This third equation, allows one to compare various materials for the bars. This is important since two options for bar material are aluminum and titanium. A higher angular velocity is achieved if the material of the bar has high yield stress and low density shear modulus [1]. These guidelines are best followed by titanium; nonetheless difficulty arises when producing a pulse with amplitude sufficiently high for the shearing stress to reach the yield stress of the titanium [1].

Test Specimens

The specimen shape currently in use by the AFRL, as displayed in Figure 18, is a thin-walled tube placed between hexagonal flanges, inserted in matching hexagonal sockets at the ends of the incident and transmitter bars. This insertion is complimented with set screws along the flanges of the specimen that maintain the connection with the bar in place. Experiments show that this configuration prevents relative rotation of the specimen and the bar. However, it is the AFRL's case that when using specimen materials with high flow stress, relative motion in the specimen/bar interface is present. This is not simply resolved by using cemented connections because it is not a practical solution and it does not work with high flow stress materials. Another note on the geometry of the specimen is that it is a short tube. This allows for a homogenous state of strain to be obtained after a few reflections of the loading pulse from the ends of the specimen [1].

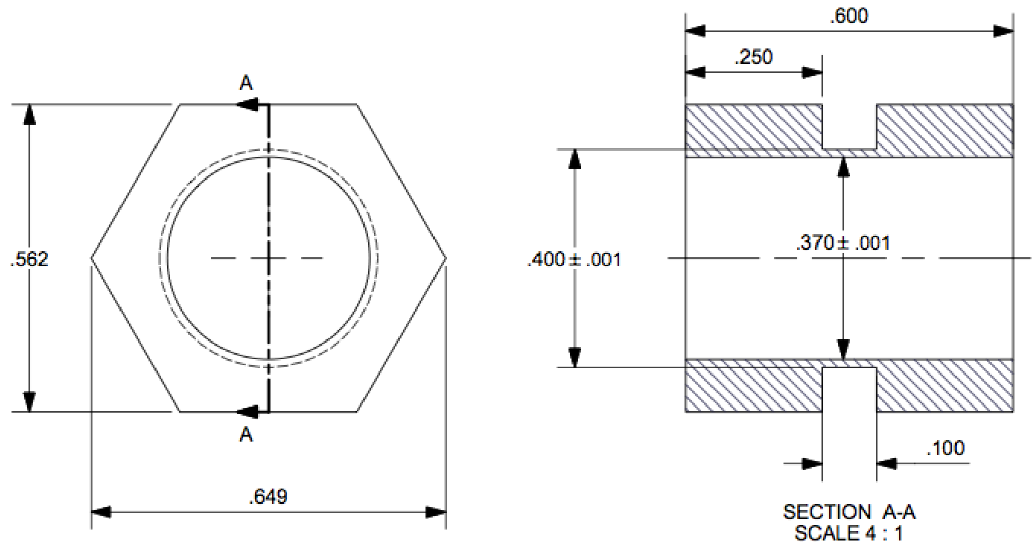


Figure 18 AFRL Tubular Specimen with Hexagonal Flange [5]

Measuring the Shear Pulses

The shear stress pulse that propagates through the incident and transmitters bars needs to be measured to know the history load and deformation of the specimen. This is accomplished through the use of strain gages located at three different points, A, B, and C, along the bar. Points A and B correspond to the midpoints of the input and output bars respectively. Point C, on the other hand, is located between the torque wheel and the clamp. At each point, there are four strain gages placed in pairs, connected in a Wheatstone bridge circuit [1]. The pairs of gages are placed so that one pair faces the other and each gage is oriented at a 45˚ angle to the axis of the bars [2]. Only the shear strains are measured due to the orientation of the gages. The strain gage bridge at point C, measures the applied stored torque to the bar.

Stress, Strain, and Strain Rate

The purpose of utilizing the Torsional Split Hopkinson Bar is to obtain the measurements from the strain gages and be able to incorporate these results to calculate the desired properties that are stress, strain, and strain rate. The following procedure and equations dictate how these properties are determined in a full-scale test for a Torsional Split Hopkinson Bar.

The average shear strain rate in the specimen as a function of time is given in equation 4.

$$\dot{\gamma}_s = \frac{r_s}{L_s}\left[\dot{\theta}_1(t) - \dot{\theta}_2(t)\right] \quad \text{Equation 4}$$

where r_s is the radius of the specimen, L_s is the length of the specimen, and $\dot{\theta}_1$, $\dot{\theta}_2$ are the angular velocities of the ends of the specimen. Also, the strain rate of the specimen as a function of strain of reflected pulse is obtained by equation 5.

$$\dot{\gamma}_s(t) = \frac{r_s}{L_s}\frac{2c}{r_b}[-\gamma_r(t)] \quad \text{Equation 5}$$

However, if one wishes to determine the strain rate at a time t, then equation 6 must be implemented.

$$\dot{\gamma}_s(t) = \frac{c}{r_b}\frac{r_s}{L_s}[\gamma_A(t - t_A) - \gamma_A(t - t_A + 2t_B) - \gamma_B(t + t_B) - \gamma_C(t + t_C) \quad \text{Equation 6}$$

The shear strain in the specimen is determined by following equation 7.

$$\gamma_s(t) = \int_0^t \dot{\gamma}_s(t)dt \quad \text{Equation 7}$$

Lastly, to calculate the shear stress of a thin walled tube, equation 8 is employed.

$$\tau_s = \frac{Gr_b^3}{4r_s^2 t_s}\gamma \quad \text{Equation 8}$$

In order to obtain results for stress and strain when a torsional test is performed with the prototype built for this project another set of equations must be employed. This is because only two strain gages are utilized at the midpoints of the incident and transmitter bars. Also, a relationship between voltage, time, and shear strain needs to be established since the experimental data is acquired in terms of time and voltage. Equation 9 gives this relationship for a Full-Bridge Type I configuration, which uses four active gages with adjacent gage pairs subject to equal and opposite strains [18].

$$\varepsilon = \frac{-V_r}{GF} \qquad \text{Equation 9}$$

where ε is strain in the form of micro-strain, GF is the gage factor, and V_r is best understood in equation 10.

$$V_r = \frac{V_{strained} - V_{unstrained}}{V_{ex}} \qquad \text{Equation 10}$$

where $V_{strained}$ corresponds to the voltage when strain is being applied, $V_{unstrained}$ is an initial offset voltage, and V_{ex} is the bridge excitation voltage. For purposed of this project, $V_{unstrained}$ equals zero.

Once the strain is known, it is possible to apply equation 11 to calculate the shear strain γ_{xy} present in the system.

$$\gamma_{xy} = \left(\varepsilon_{xy} + \varepsilon_{yx}\right) = 2\varepsilon_{xy} \qquad \text{Equation 11}$$

The strain rate and shear stress calculations are performed using equations 5 and 8 (page 21) respectively.

Structural Analysis

Analysis for the complete assembly of the prototype dictates the functionality of the design of the model and proper understanding of the equations driving these experimental tests. More attention is given to the specimen since the test results of stress-strain data determine if relative motion is present and thus if the design is successful or not. The structural analysis consists in simulating various configurations (designs of 12, 10, 8, and 6 set screws) to compare them and verify which design is best.

The idea is to provide the Air Force Research Lab with a design for a complete set of bars, incident and transmitter, with the proposed design already incorporated. Ideally, the location of the strain gages would not need any modification since sizing remains unchanged.

Regardless of which selection is made, material options for the bar must be considered as mentioned in the previous section.

The design is tested by means of a prototype to be discussed in future sections. It is important to note that an issue arises when using a model; being that the distance between the gage station and the specimen must be enough so no abnormality is present when measuring the data. Abnormality may be the interference or overlap of the incident and reflected pulses [1]. Studies to represent this phenomenon follow.

In order for the torsional wave that is propagating through the bar not to undergo reflection, the mechanical impedance of any mechanical connection device must be equal to the mechanical impedance of the bars. In other words, the product of density, speed of wave and polar moment of inertia must remain constant between the bar and the connection device [1].

A structural study is performed to the bar, specimen, and set screws in the form of manual calculations to prove the functionality of the prototype and its ability to sustain the testing loads and understand their behavior. These values are also compared with computational results.

Behavior of Bars

Table 1 Initial Parameters for Bars

Torque	T	600 in lb
Length	L	6 in
Second Polar Moment	J	4.08x10^-8 in^4
Shear Modulus	G	3770 kpsi
Yield Strength	Sy	40000 psi

The angle of twist in the elastic range is given by equation 12.

$$\phi = \frac{TL}{JG} \qquad \text{Equation 12}$$

The maximum shearing strain is calculated with equation 13.

$$\gamma_{max} = \frac{r\phi}{L}$$ Equation 13

The torque on the bars,

$$T_{ut} = \frac{J\tau_{ut}}{r}$$ Equation 14

The torque at yielding strength is given by,

$$T_y = \frac{J\,\tau_y}{r}$$ Equation 15

The maximum stress at the applied torque is determined following equation 16.

$$\tau_{max} = \frac{Tr}{J}$$ Equation 16

Very importantly, is the calculation of the von Mises stress, obtained by applying equation 17.

$$\sigma' = (\sigma_x^2 + 3\tau^2)^{1/2} \quad \sigma_x = \frac{4P}{\pi d^2} \qquad \tau = \frac{16T}{\pi d^3}$$ Equation 17

Lastly, the factor of safety for the bars is obtained by means of equation 18.

$$n = \frac{S_y}{\sigma'}$$ Equation 18

The results for the structural study of the bar are represented in Table 2.

Table 2 Calculations for the Bars

ϕ	0.00972 rad
ϕ	0.557 deg
γ_{max}	8.1x10^-4
T_{ut}	736.27 ft.lb
T_y	654.46 ft.lb
τ_{max}	3058.10 psi
σ_x	0
τ	3055.77 psi
σ'	5292.75 psi
n	7.55

Behavior of the Specimen

Table 3 Initial Parameters for Specimen of 300m Steel

Torque Applied	T	600 in.lb
Specimen Length	L	0.100 in
Second Polar Moment	J	6.733x10^4 in^4
Shear Modulus	G	11600 kpsi
Specimen Radius	c	0.2 in
Shear Strength	τ_{max}	30000 psi

The angle of twist for the specimen is calculated following equation 19.

$$\phi = \frac{TL}{JG} \tag{Equation 19}$$

The shear stress at the applied torque is obtained with equation 20.

$$\tau = \frac{Tc}{J} \tag{Equation 20}$$

Lastly, the maximum torque is obtained following equation 21.

$$T_{max} = \frac{J\tau_{max}}{c} \tag{Equation 21}$$

The results for the structural study of the specimen are represented in Table 4

Table 4 Calculations for the Specimen

ϕ	0.440 deg
ϕ	0.00768 rad
τ	178.3 kpsi
T_{max}	8.41 ft.lb

Behavior of the Set Screw

Table 5 Initial Parameters for a Set Screw of Alloy Steel

Length	L	0.003 in
Diameter	D	0.112 in
Force	P	2135.23 lbf
Area	A	0.0098 in^2
Modulus of Elasticity	E	30457925 psi
Yield Strength	S_y	89984.6 psi

The deformation of each set screw is given by equation 22.

$$\delta = \frac{PL}{AE} \qquad \text{Equation 22}$$

The strain exhibited by each screw is determined using equation 23.

$$\varepsilon = \frac{P}{AE} \qquad \text{Equation 23}$$

The stress is calculated by equation 24.

$$\sigma = E\varepsilon \qquad \text{Equation 24}$$

The factor of safety for the set screws is given by,

$$n = \frac{S_y}{\sigma'} \qquad \text{Equation 25}$$

where the Von Mises stress, σ′, is given by Equation 26

$$\sigma' = \frac{32M}{\pi d^3} \qquad \text{Equation 26}$$

The results for the structural study of a set screw are represented in Table 6.

Table 6 Calculations for a Set Screw

δ	$2.135 * 10^{-5}$ in
ε	0.007117
σ	$21.677 * 10^{4}$ psi
n	2.05
M	6.0405 in.lb
σ'	43794.43 psi

By the results displayed in Table 6, it can be observed that the deformation of the set screws under the load to be applied will generate a deformation not large enough to give an anomaly reading in the data. Therefore these deformations can be neglected. At the same time, the factor of safety of the setscrews is greater than 1, meaning that the set screws are not going to experience failure during the experiments.

Finite Element Analysis

A finite element analysis is performed to the prototype assembly, the setscrews, and specimen to simulate a torsional test and obtain results for resultant displacement, von Mises stress, and strain. This gives some insight and allows for a comparison between the simulations and calculations. Additionally, the results determine how much torsion the bar configuration can sustain and how it is affected when loads are applied. This same concept applies to the specimen and the setscrews, even though it is expected that the specimen fails and fractures. The idea behind this analysis is to obtain a preview of what can occur during actual testing of the prototype. The simulations also serve as a guide for determining which configuration experiences the least amount of relative motion. Computational analyses were performed using SolidWorks for static studies.

The simulations for the prototype corresponds to a torsional load of 600 lb-in. applied to the each face of the specimen on opposite directions. The setscrews that attach the specimen to the hex pocket are also simulated and resist 5 lb-in torque and an axial force of 90 lb. For this case, an axial force of 50 lb was applied per set screw. Figure 19 is a view of the prototype and specimen with the loads for the simulation. Aluminum 6061 alloy was the material used for the bars and its characteristics are summarized in Table 9.

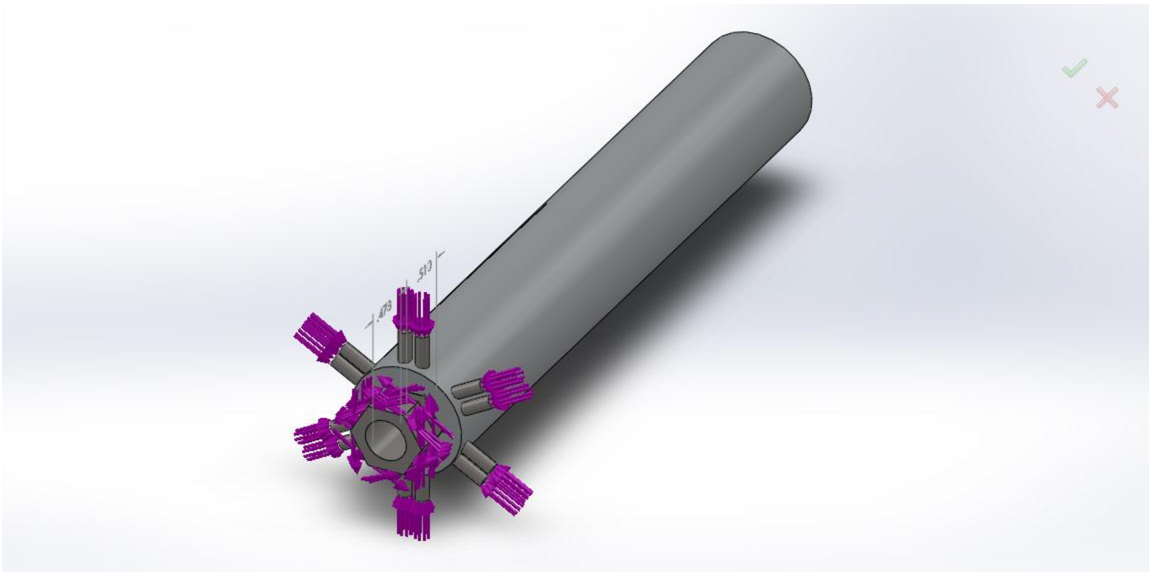


Figure 19 Simulation Loads

Table 7 Study Information for Simulation

Study name	Stress
Analysis type	Static
Mesh type	Solid Mesh
Thermal Effect:	On
Thermal option	Include temperature loads
Zero strain temperature	298 Kelvin
Include fluid pressure effects from SolidWorks Flow Simulation	Off
Solver type	FFEPlus
Inplane Effect:	Off
Soft Spring:	Off
Inertial Relief:	Off
Incompatible bonding options	More accurate (slower)
Large displacement	Off
Compute free body forces	On
Friction	Off
Use Adaptive Method:	Off

Table 8 Mesh Information

Mesh type	Solid Mesh
Mesher Used:	Standard mesh
Automatic Transition:	Off
Include Mesh Auto Loops:	Off
Jacobian points	4 Points
Element Size	0.0862817 in
Tolerance	0.00431408 in
Mesh Quality	High
Remesh failed parts with incompatible mesh	Off

Table 9 Material Properties of the Bar

Name:	6061 Alloy
Model type:	Linear Elastic Isotropic
Default failure criterion:	Unknown
Yield strength:	7999 psi
Tensile strength:	17997 psi
Elastic modulus:	10000 ksi
Poisson's ratio:	0.33
Mass density:	0.0975 lb/in^3
Shear modulus:	3770 ksi
Thermal expansion coefficient:	2.4e-005 /Kelvin

Table 10 Material Properties of Each Set Screw

Name:	Alloy Steel
Model type:	Linear Elastic Isotropic
Default failure criterion:	Unknown
Yield strength:	89985 psi
Tensile strength:	104982 psi
Elastic modulus:	30457925 psi
Poisson's ratio:	0.28
Mass density:	0.27818015 lb/in^3
Shear modulus:	11458 ksi
Thermal expansion coefficient:	1.3e-005 /Kelvin

Displacement Study

A study was devoted to the analysis of resultant displacement in order to calculate how much the specimen moves inside the hex pocket during a torsional test. This is important because it determines if the provided design is successful or not since a grand displacement signifies relative motion. The displacement analysis, along with those for von Mises stress and strain, were performed to the different configurations of set screws (12, 10, 8, and 6 set screws) in order to compare them and establish which is more promising. It is expected that the design with 12 set screws will provide better results since it offers the most surface contact with the specimen, diminishing the possibility of relative motion during the propagation of a shear pulse.

Table 11 Displacement Results for All Configurations

Type of Configuration	Min.	Max.
12 Set Screws	0 in	0.0202732 in
10 Set Screws	0 in	0.0206292 in
8 Set Screws	0 in	0.0212136 in
6 Set Screws	0 in	0.0205572 in

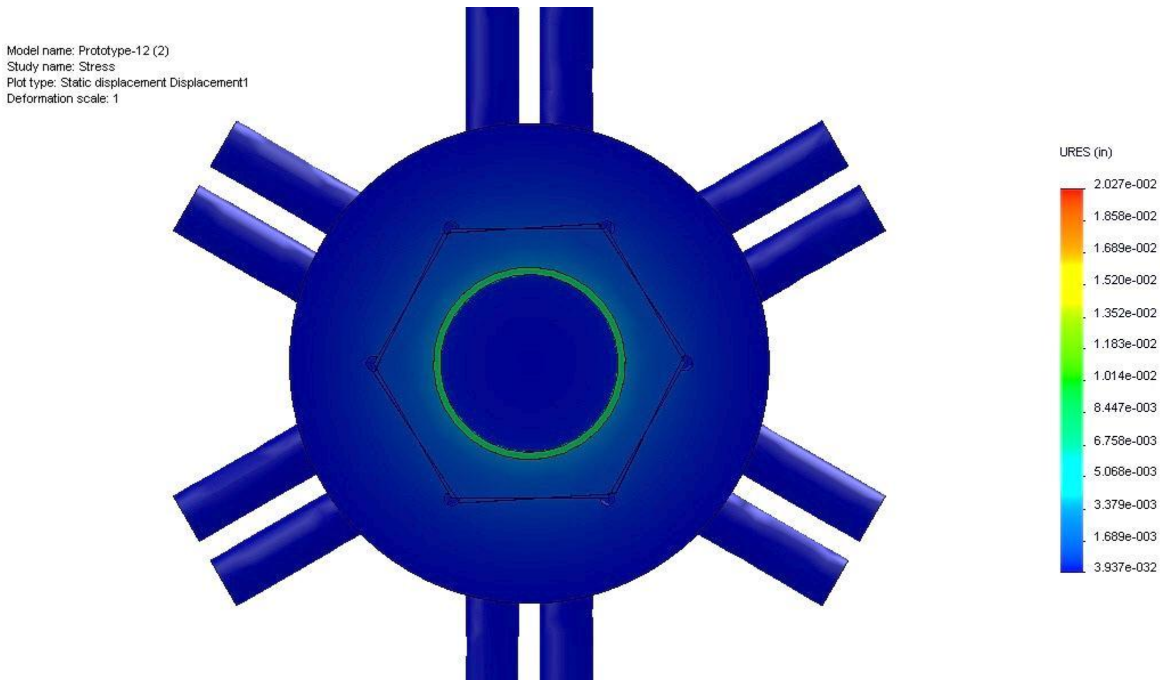


Figure 20 Displacement Study for 12 Set Screws - Front View

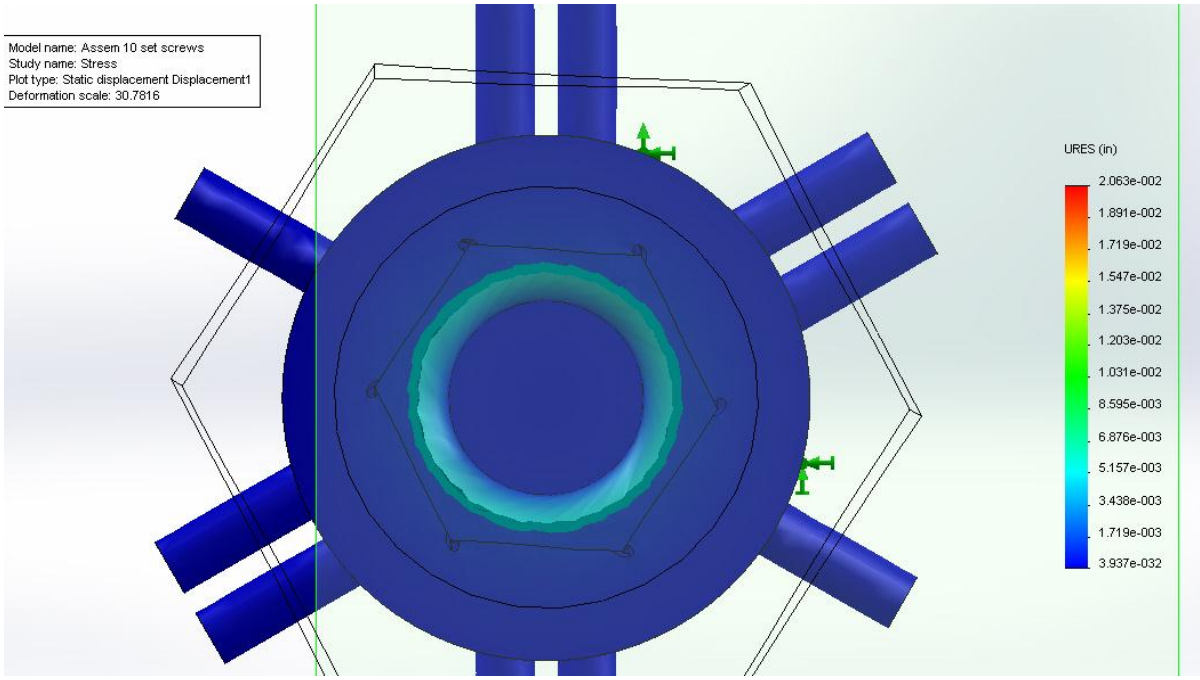


Figure 21 Displacement Study for 10 Set Screws - Front View

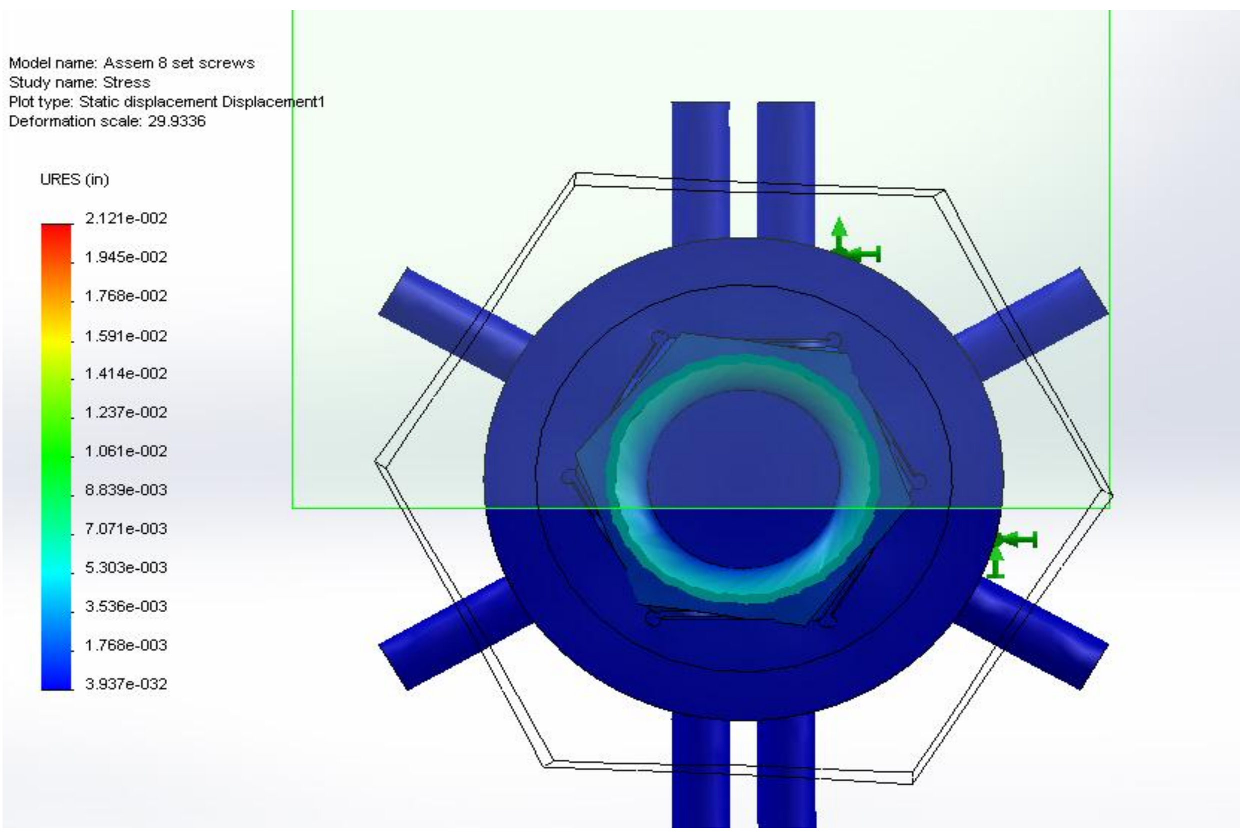


Figure 22 Displacement Study for 8 Set Screws - Front View

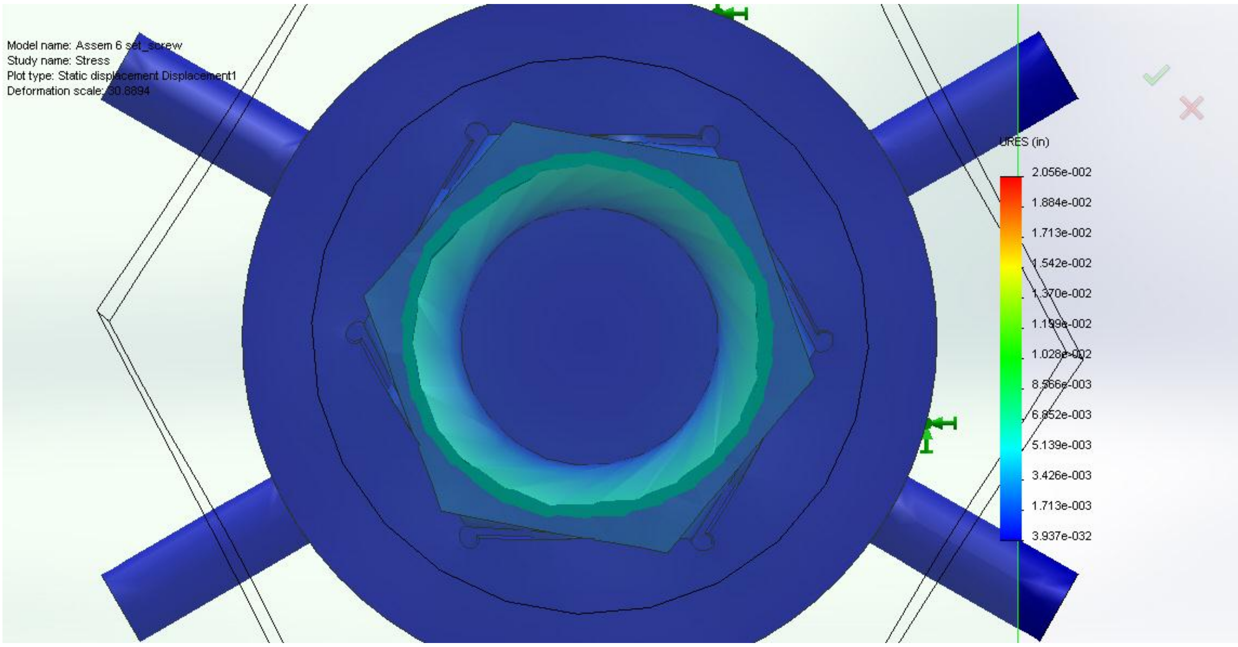


Figure 23 Displacement Study for 6 Set Screws - Front View

The simulation plots (Figures 20-23) reveal how much the specimen moves when a torsional load is applied. This occurs even though the set screws are applying a force to restrain this motion from taking place. The importance, however, is to see with which configuration of set screws there is the least amount of displacement. Table 11 displays the computational results for the minimum and maximum displacements and it is possible to determine that the configuration of twelve set screws reveals the least amount.

For all other simulation studies refer to Appendix C.

Set Screw Study

A simulation is performed to the set screw since it is a major component in the prevention of motion between the specimen and the bar. Computational analyses were carried out to obtain results for shear stress, principal stress, resultant displacement, between several others. These characteristics allow determining how much load the set screw can sustain and what occurs when a torsional load is applied. For purposes of this study, the set screw was modeled as a pin since an actual set screw is too difficult to simulate with the entire prototype assembly.

A resultant displacement study reveals that the setscrew moves a maximum of 0.000227606 in. and this is present in the face that is in contact with the specimen.

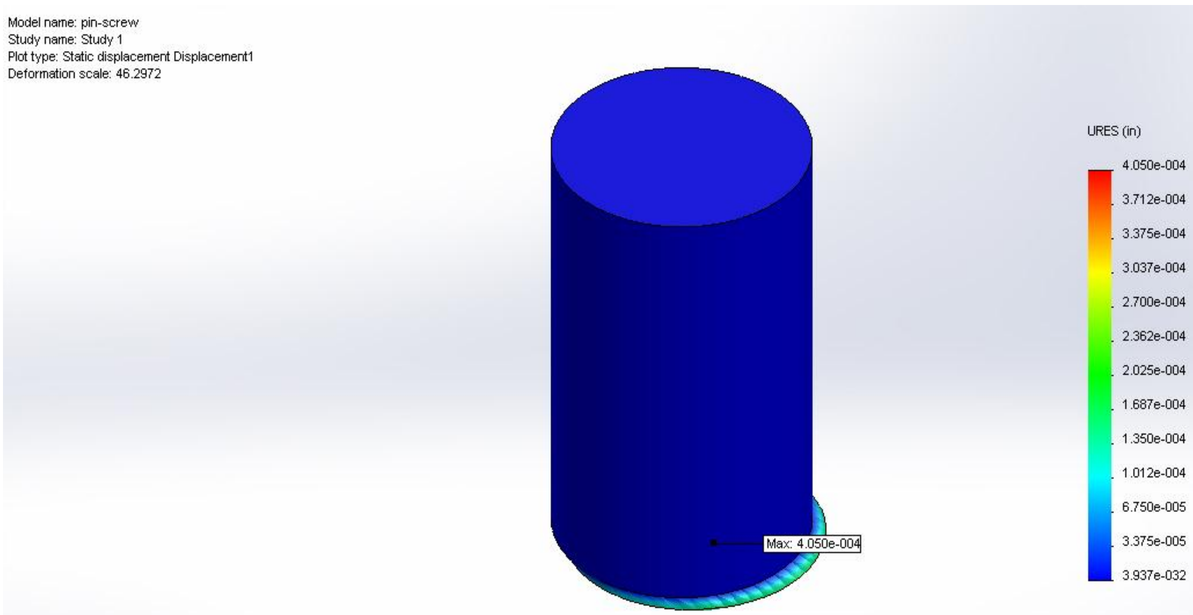


Figure 24 Displacement Study for a Set Screw

Specimen Study

A simulation of the torsional test is performed to the specimen to understand the effects of the applied torsion. The specimen suffers a great deal of distortion, which leads to failure and fracture. Figures 25-27 represent studies of stress, displacement, and strain. It can be seen that most of the stress and strain are concentrated in the center of the specimen, which is the thinnest section of the piece. Due to how thin the middle is, the specimen experiences failure there.

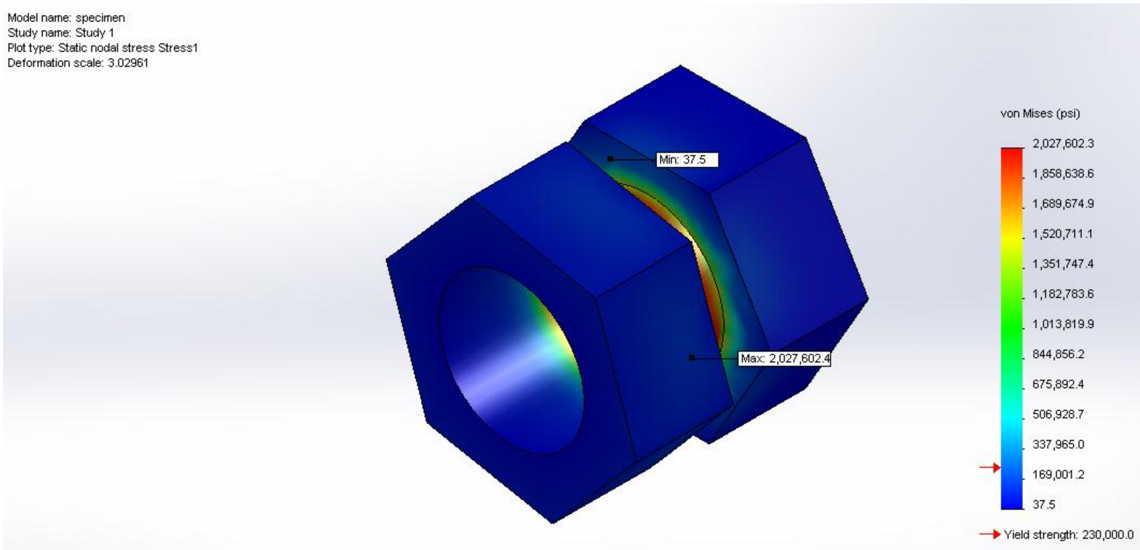


Figure 25 Von Mises Stress Study for Specimen

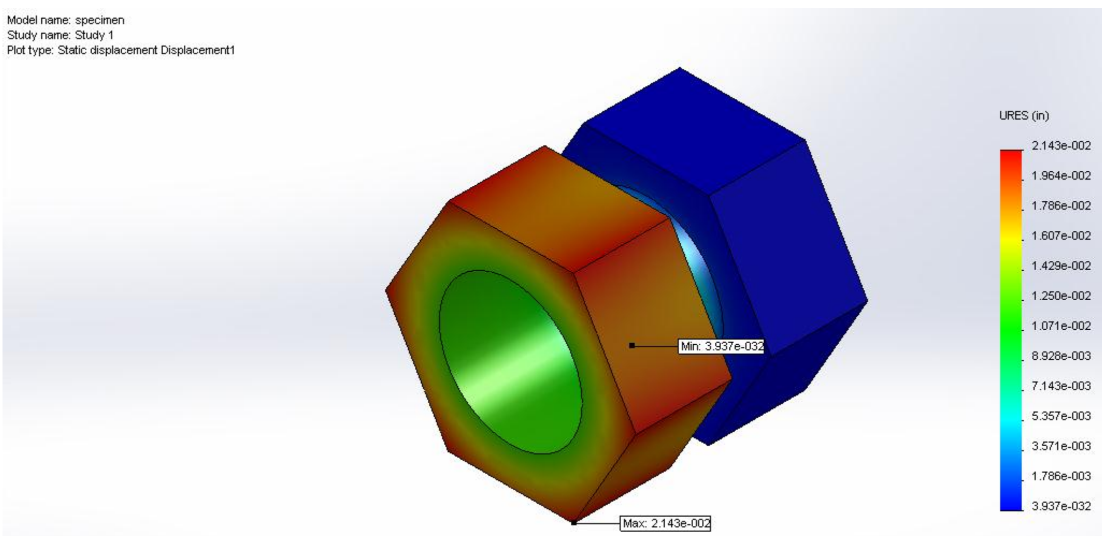


Figure 26 Resultant Displacement Study for Specimen

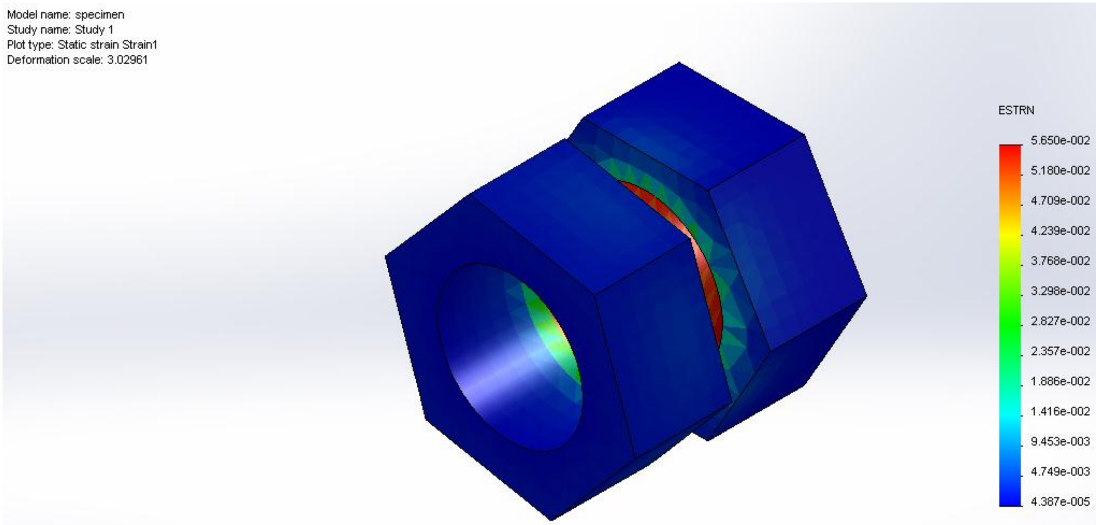


Figure 27 Strain Study for Specimen

Bar Study

A simulation is also performed to the actual bars used in the prototype to analyze their properties in order to verify that they can withstand the testing loads and torsion. Results are obtained for von Mises stress, resultant displacement, and strain, which are characteristics considered vital in the understanding of the prototype. Results show that the maximum results for von Mises stress is 65590.3 psi, the resultant displacement is 0.00209 in. and the maximum strain is 0.00165. These results show that the bar can withstand the experimental loads.

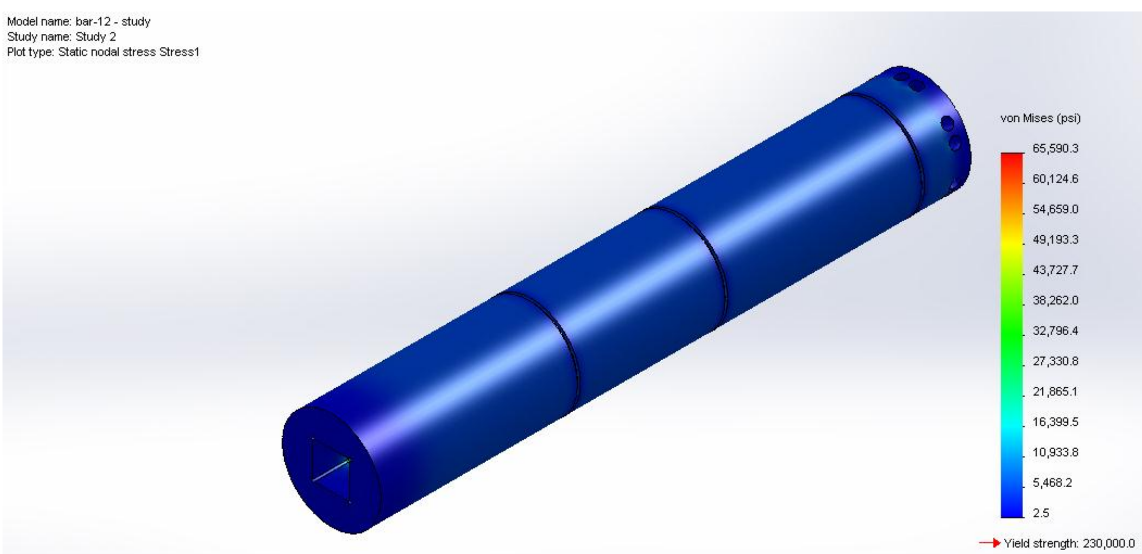


Figure 28 Von Mises Stress Study for Bar

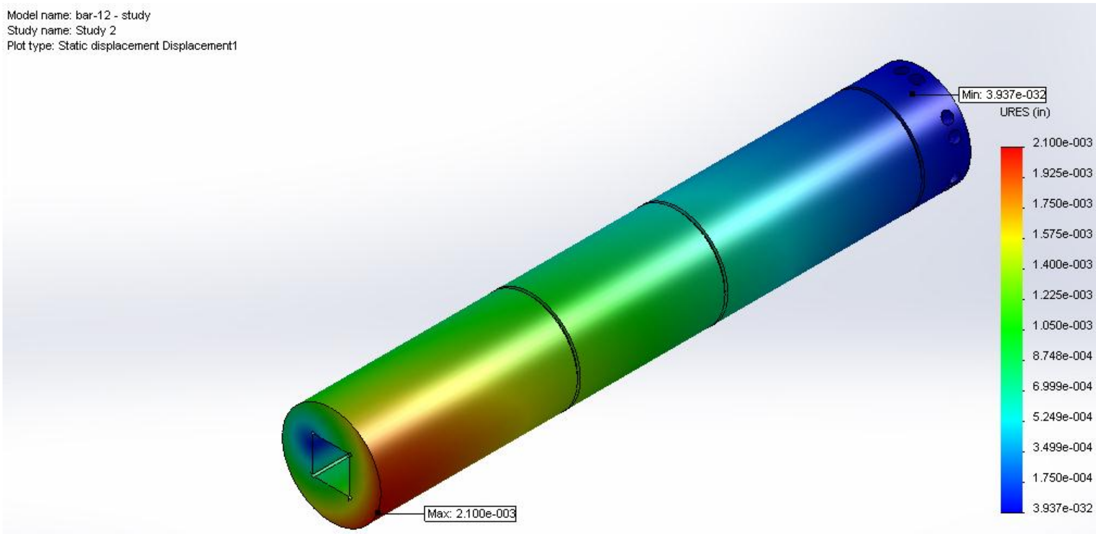


Figure 29 Resultant Displacement Study for Bar

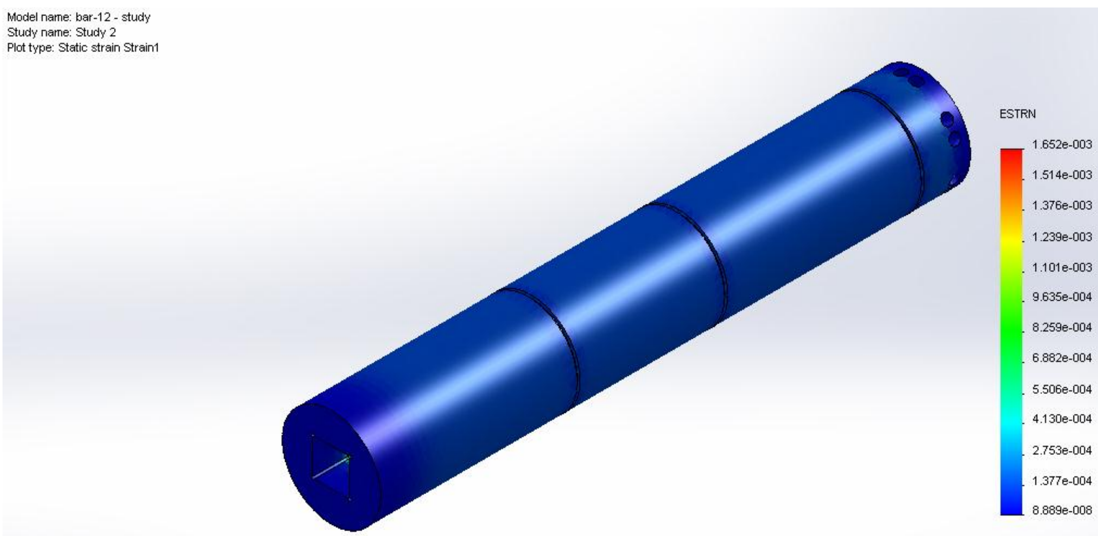


Figure 30 Strain Study for Bar

Prototype

The prototype serves as a means to test the solution to the relative motion present in the Torsional Split Hopkinson Bar during high strain-rate testing of materials. The simplified working model of the AFRL's Kolsky bar includes the key components (incident and transmitter bars, hexagonal pocket, setscrews, strain-gages, and pillow blocks). This model is utilized for specimen testing to obtain data from which conclusions can be made regarding the elimination of relative motion. The following information describes the various selections for the development of a prototype and assembly process.

Assembly

The functional prototype with which all the tests are going to be conducted was built with commercial components. The majority of the components were obtained through McMaster-Carr Supply Company, with the exception of the strain gages purchased from Micro-Measurements, Inc.

The base of the prototype is a steel structure made by the process of mold casting. It is important for this base to be supportive enough to withstand all the loads that the apparatus is going to be subjected to. This base is where the pillow blocks are going to be attached as shown in Figure 31. The threaded holes are spaced according to the prototype dimensions and those of the pillow blocks. Refer to Appendix A for the detailed drawings for all of the prototype components.

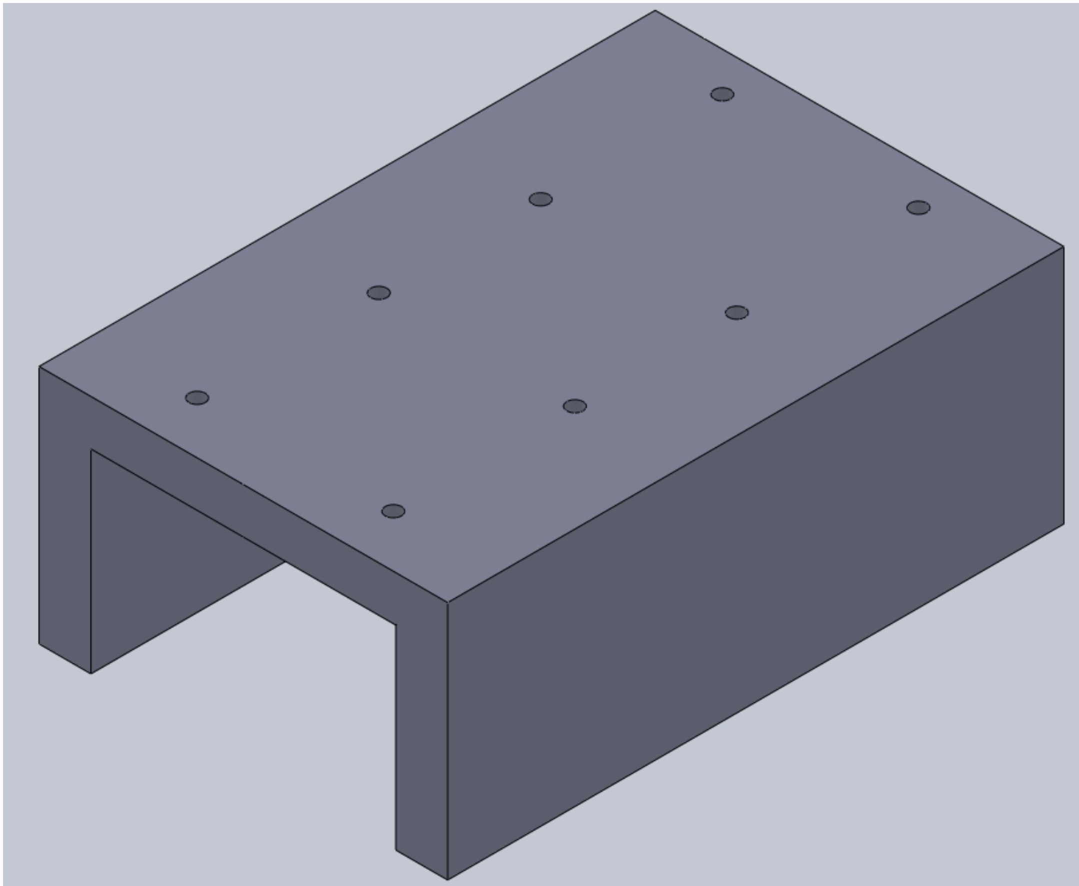


Figure 31 Prototype Base

The pillow blocks used to mount the incident and transmitter bars are cast iron based-mounted Babbitt-lined bearing split, for 1 in. shaft diameter (Figure 32). With these pillow blocks, the shafts are able to rotate freely and provide support throughout the tests. In order to fix the transmitter bar, it is necessary to adjust the pillow block on the far right end of the model.

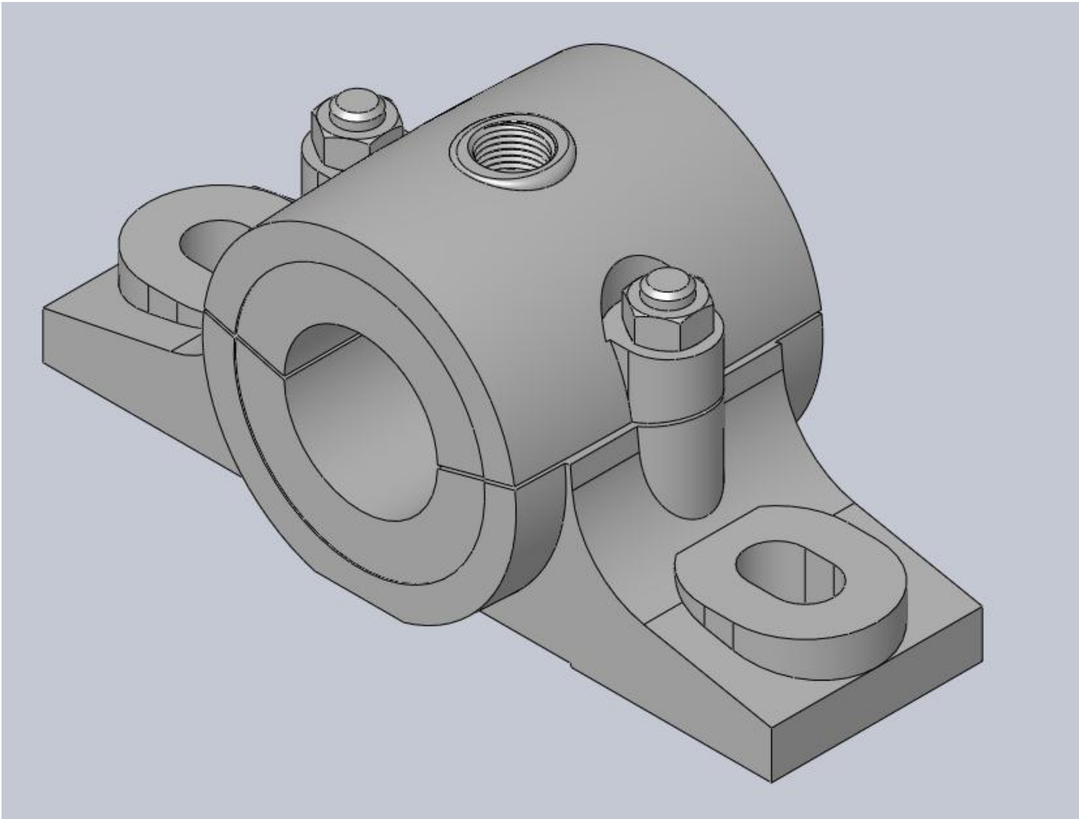


Figure 32 Pillow Blocks

In the same manner, the corresponding screws to attach the pillow blocks to the base are selected. These screws are black-oxide alloy steel socket head cap screws with 5/16-18 thread and 1-3/8 in. length.

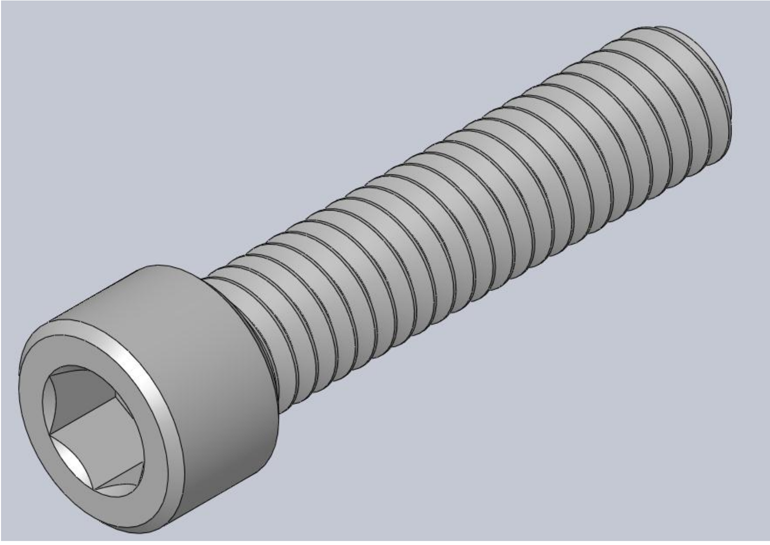


Figure 33 Screws for Pillow Blocks

Strain Gages

The equipment for obtaining the measurement of the shear pulse consists of a series of strain gages connected in a Wheatstone bridge type circuit. The TSHB has a total of three strain gage circuits. Two are connected at the midpoints of the incident and transmitter bars and they measure the transmitted and reflected shear pulse. The remaining circuit is connected between the torque wheel and the clamp and is responsible for the measurement of the applied torque to the bar. The way each Wheatstone bridge circuit is connected is by working in pairs. The first pair is connected diametrically on the axis of the bar, one strain gage is 45° from the axis and the other is -45°. The second pair of strain gages is connected in the same manner but in the opposite direction of the bar (facing down).

An alternate method for connecting these circuits is needed to adapt the testing procedure with the prototype. This is because the testing model will be reduced in size and certain modifications, such as the way the torque is applied and how the bars are placed, also take place. Due to this, the shear pulse must be measured correctly as it propagates through the entire model. In order for this to occur, adequate strain gages that comply with operating temperature, test duration, and strain gage resistance need to be selected.

Prior to selecting these devices, it was decided that rather than three sets of strain gages, only two would be implemented. This choice is due to the size reduction of the Kolsky bar model. Two sets of strain gages, one in each of the midpoints of the incident and transmitter bars, will measure the torsional wave that is released from the torque wrench reaching the specimen and reflecting back through the bar. The use of two sets also allow for the conversion of experimental data to stress vs. strain curves for each test made.

One of the main tasks regarding strain gages is making sure they are properly connected to the bar configuration. This action can result being difficult since they have to be placed at a particular angle and welding needs to take place to make proper connections. All of these alterations not only may affect testing results, but can contribute to the fatigue of these devices. In order to avoid this, a kit of strain gages was selected in which the gages already come in pairs at the necessary angles (45° and -45°). The type of strain gage selected is a shear/torque rosette of model CEA-06-187UV-350 that provides ideal functionality for the desired testing technique and fits into the configuration due to is 0.187 in. length. This CEA series is used for general stress analysis purposes. “These polyimide encapsulated constantan gages feature large, rugged, copper-coated tabs. This construction provides optimum capability for attaching lead wires directly to the tabs, eliminating the need for separate terminals” [16]. The selected type of gage has a range of operating temperatures and a gage factor that allow its use. Additionally, the strain gage resistance of 350 Ohms aids in the decrease of heat generation, reduction of lead wire effects, or the improvement of signal to-noise ratios in the gage circuit [16].

Prior to mounting the strain gages to the prototype, a procedure for installing them must be followed to ensure proper function. The steps to do this include measuring the location of the gages and surface preparation, where the surface of bar is degreased, abraded with a grinder and a conditioner, and neutralized to bring the surface to an optimum alkalinity. This is followed by mounting the gages and applying a bonding agent and an adhesive (glue).

Refer to Appendix B for parts information.

Material Selection

Selecting the right material for the incident and transmitter bars also dictates the success of this project since the torsional wave propagates through that medium. The most common materials used for this application (Kolsky bar) are aluminum, steel, and titanium. Bars made of aluminum are easy to use and will work for most applications. What makes aluminum one of the recurrent materials for this application is its low shear modulus and low density, which allow for greater angular velocity in order to provide for a more elastic torsional wave.

Another option is bars made of titanium, which is a material that produces a high angular velocity; however it is difficult to produce a desired elastic torsional wave due to the high shearing stress. Titanium allows for the testing of materials with high flow stress, for instance different steels. However, to obtain proper results the torque needs to be recalculated and increased to reach an appropriate angular velocity for the experiment [1]. Although titanium has great qualities such as an elevated strength-to-weight ratio and possesses a high melting point (higher than 3,000°F), it results difficult to work with and is of elevated cost in comparison to other materials. When comparing titanium with aluminum, the latter produces a higher angular velocity with a less amount of torque and provides for a wide variety of grades to select from [2].

Due to the analysis of the materials mentioned previously, anodized aluminum 6061-T6 is the material that can provide the desired results for the application in question since it provides medium to high strength requirements. This is a standard structural alloy and contains magnesium and silicon. Additional properties pertaining to this material are its great resistance to corrosion and its versatility as a heat-treatable alloy, not to mention that it possesses good toughness characteristics [9]. Additionally, the desired 6061 alloy is anodized, which means that there is an additional layer of protection. Lastly, aluminum 6061 provides good machinability characteristics and is easily welded. Given that it is a softer material and can be obtained in the specific dimensions (established by the AFRL) directly from the supplier, it results in being a convenient option. Table 12 summarizes the properties for the aluminum 6061 alloy.

Table 12 Material Properties of 6061-T6 Aluminum Alloy [12]

6061-T6 Aluminum		
Physical and Mechanical Properties	Density, lb/in3	0.0975
	Ultimate Tensile Strength, psi	45,000
	Yield Strength, psi	40,000
	Brinell Hardness	95
	Rockwell Hardness	B60
	Shear Strength, psi	30,000
	Shear Modulus, Ksi	3,770
	Modulus of Elasticity, Ksi	10,000
	Elongation at Break	12%
	Poisson's Ratio	0.33
Chemistry	Aluminum (Al)	95.8 - 98.6%
	Chromium (Cr)	0.04 - 0.35%
	Copper (Cu)	0.15 - 0.40%
	Iron (Fe)	0.70%
	Magnesium (Mg)	0.8 - 1.2%
	Manganese (Mn)	0.15% max
	Silicon (Si)	0.4 - 0.8%
	Zinc (Zn)	0.25%

Set screw Selection

Once the material for the Kolsky bar has been established, it is possible to begin the process of selecting the set screws that will provide the best surface contact possible while fitting into the configuration and can withstand the testing conditions. The criteria for screw selection mainly consist on the material, the dimensions (diameter and length), and the threading of the piece. Whichever set screw is selected, must be flat ended rather than pointy or sharp, since this allows for better surface contact with the specimen, therefore reducing relative motion in this interface.

A set screw is one of the various types of screws available and it is characterized by being threaded along its entire length. It is commonly used to prevent a shaft from rotating [9]. In this case, set screws are used to secure the specimen from moving.

As previously established, the desired screw must be of flat point. The selection process begins by focusing on flat point hex socket set screws, which are very good when making adjustments frequently. Additionally, set screws barely cause damage if any to the surface they make contact with.

The first factor to take into consideration is the dimension. This is because a relatively large screw diameter allows for a small tolerance between them, weakening the bar. This is especially true when dealing with two set screws per face of the hexagonal pocket (12 set screws configuration). Analysis of the available dimensions gives forth to the selection of a diameter of 0.112 in. This size is small enough to fit two setscrews per hexagonal face.

The following criterion for screw selection is the material. Focus is given to choosing a material that can be obtained in the necessary dimensions and is of desirable properties. A very good option is steel since it offers resistance to corrosion and provides strength, however one selects an alloy steel, in this case it will be black-oxide alloy steel. Stainless steel was not selected because the strength is considerably less than alloy steel [9].

Threading is also a factor when selecting screws, however for the purposes of this model, this characteristic is not predominant. The selection is based on the thread in which the previous constraints are satisfied. The thread results to be a 3A thread fit, specifically #4-40.

The selection process must be done following a hierarchy in order to guarantee that the essential criteria are satisfied. The rest are selected among the best of the available options. Due to this the choice is self-locking black alloy steel screws. These can be reused and have a nylon patch on the threads that keeps them from vibrating loose.

Torque Wrench

In order to be able to conduct the test the torsion needs to be applied in the incident bar and is characterized by its rise in time, shape, amplitude, and duration. The most common method, used by AFRL, is to generate the torsional wave as a rapid release of stored torque. Such torsion is produced by a rotating wheel, attached at the end of the incident bar with a hydraulic system of cable and pulleys that applies a pure couple to the wheel. By using the torque wheel, the stored torque is deficient of any bending moment or axial force that may create a disturbance on the torsional wave. Once the torque is produced it is stored between a tightened clamp and the loading end of the bar (Figure 34) [1].

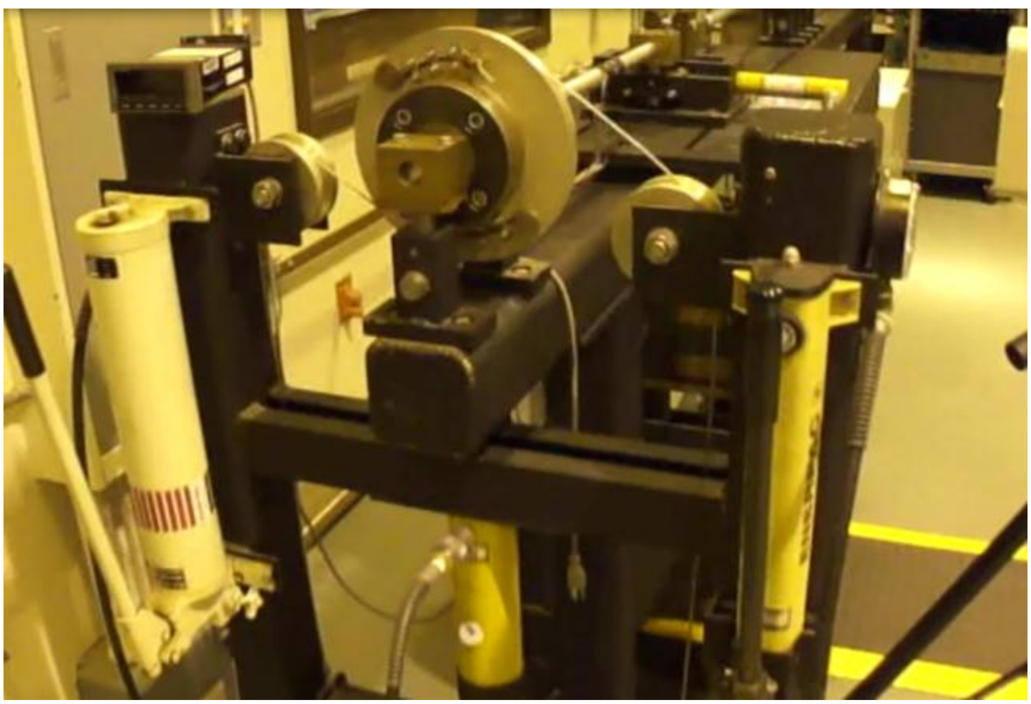


Figure 34 Torque Wheel and System of Pulleys [8]

For purposes of the prototype, the torsional wave is generated by means of a torque wrench rather than a torque wheel. The use of a torque wrench will in turn eliminate the need of the clamp mechanism to store the torque, since the torque wrench will precisely apply the amount of torque needed.

Torque wrenches are most used to tighten screws and bolts with the right amount of tension and loading to meet proper specifications of any particular application. There are different types of such wrenches that may be used for the prototype of the Kolsky bar; these include the beam, electronic wrenches, and click types.

The beam type wrenches are the simplest of the torque wrenches. This mechanism consists of a long lever arm between the handle and the wrench head, made of a material, which bends elastically in response to the applied torque. A second, smaller bar with an integral mechanical indicator is also connected to the head; this is never subjected to torque and thus maintains a constant position with respect to the head. When no torque is applied to the lever arm, the indicator rests parallel to the lever arm. A calibrated scale is fitted to the handle so that an applied torque and an associated bending of the main lever cause the scale to move under the indicator. When the desired torque is reached as shown by the indicator, the operator stops applying force [15].

Electronic torque wrenches obtain the measurements with a strain gage attached to the torsion rod. The signal generated is converted by the transducer to the required unit of force (N·m, lbf·ft) and is shown on the digital display. A number of different readings can be stored for documentation or quality assurance purposes [15].

The click type torque wrench possesses a calibrated clutch mechanism, which allows for a better method to produce torque. When the desired torque is reached, the clutch slips, transmitting the desired torque and preventing additional tightening. The most common form consists of a ball detent and spring, with the spring preloaded by an adjustable screw thread, calibrated in torque units. The ball detent transmits force until the preset torque is reached, at which point the force exerted by the spring is overcome and the ball clicks out of its socket. This design provides greater precision and a positive action at the set point [15].

Figure 35 Click Type Torque Wrench [15]

The click type torque wrench is selected for the prototype since it gives a high accuracy and repeatable action without recalibrating, which allows for continuous testing with the same settings. Furthermore, it provides a push-button socket release that helps latch to the incident bar to prevent the creation of moments or axial forces during testing.

Dimensions

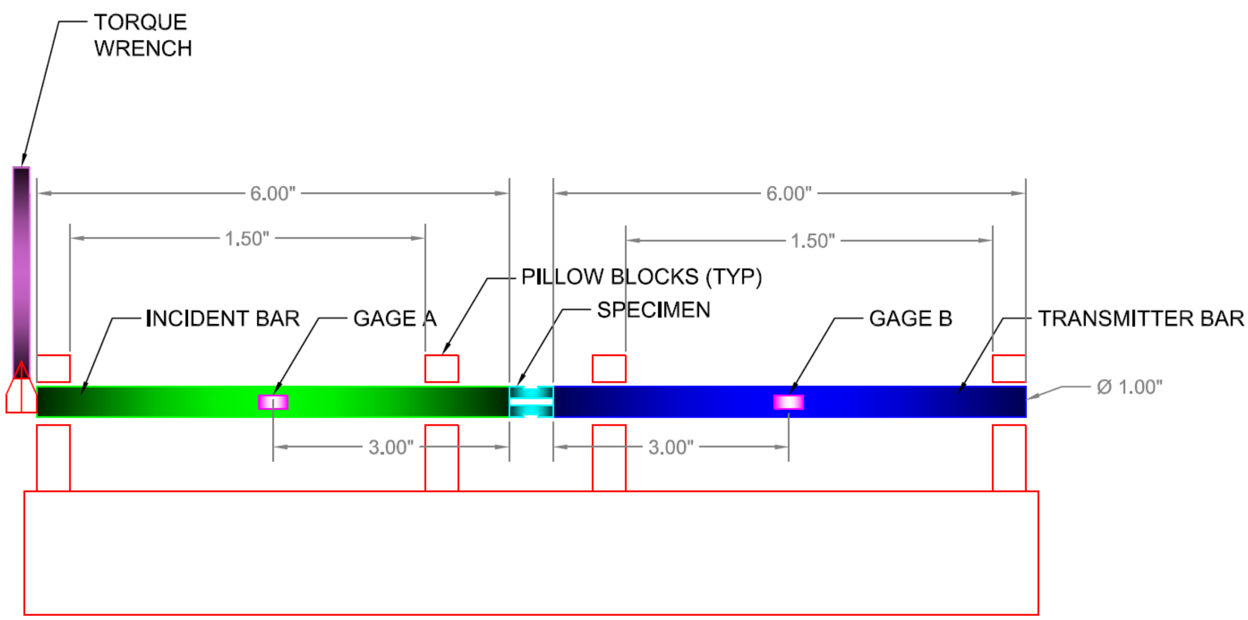


Figure 36 Prototype Dimensions

The Torsional Split Hopkinson Bar prototype set-up is shown in Figure 36. On the right-hand side is located the incident bar which has a dimension of 6 in. long and 1 in. in diameter. In addition, the incident bar sustains the torque wrench in the far right providing the input torsion for the system. The transmittance bar, located to the left, has the same dimensions of the incident bar. Both bars are of anodized aluminum 6061 T6 alloy. The support or pillow blocks are cast iron base-mounted bearings, which provide high strength and stability with low friction qualities. The pillow blocks are spaced 1.5 in. from each other, providing sufficient space to house the gages. There are two pairs of strain gages, gages A and B, on each bar placed 3 in. from the specimen.

Machining

Cutting Tool Selection

The success in metal cutting depends on the selection of the proper cutting tool for a given work material. There is a wide variety of cutting tools of different range, performance capabilities, and properties that can be used to machine the incident and transmittance bars of the prototype. The most common materials are high carbon steels, low/medium-alloy steels, high-speed steels, cast cobalt alloys, cemented carbides, cast carbides, coated carbides, and coated high-speed steels, ranked by the cutting speed used to machine a unit volume of material. As the feed rate increases, the material removal proportion increases and the time required decreases [14].

The most important aspects of the machining process are the selection of the cutting tool material, cutting parameters, and tool geometry. All of these considerations influence the productivity of the machining operation. Some of the elements that influence the tool selection are:

- Work material characteristics, hardness, chemical and metallurgical state
- Part characteristics (geometry, accuracy, finish, and surface-integrity requirements)
- Machine tool characteristics, including the work holders (adequate rigidity with high horsepower, and wide speed and feed ranges)
- Support systems (operator’s ability, sensors, controls, method of lubrication, and chip removal)

In most machine operations the cutting speed and the feed rate restrict the tool capacities. It is necessary to keep the speed low enough to improve the tool life; otherwise productivity is compromised

The tool selected to perform the cutting application for the prototype is 1/8 in. in diameter and is made of high-speed steel which retains its cutting ability at temperatures up to 1100°F and can operate at higher speeds than regular steel tools. This type of tool is made out of a mix of vanadium (1%), chromium (4%), and tungsten (18%), which allows for the improvement of hardness and wear resistance. Tools made out of high-speed steel are widely used for drills and many types of general purpose milling cutters.

CNC Machining

The adoption of computer numerical control (CNC) machines has been the most significant development in the last 60 years. These machines increased automation and an innovation in positional feedback as well as programmable flexibility to machine products. CNC machines use a processing language to control the movement of the cutting tool, work piece, or both. The programs contain information about the machine tool and cutting tool geometry, part dimensions from rough material to finish size, and machine parameters such as speed, feeds, and depth of the cut. This type of equipment can duplicate consecutive parts with the same quality and speed as the first try [14]. Additionally, CNC machines can work with accuracies of 0.00005 in. if required, but most machines provide accuracies of at least 0.0001in. The high accuracy and precision obtained from the CNC machines improve quality and minimize the machine repositioning. The CNC fulfills the tolerances required to produce the prototype bars, producing identical bars, improving the alignment of the bars and the specimen.

In order to be able to create the hexagonal pocket in which the specimen is placed, it is necessary to perforate the corners to extract the difficult angle corners that the cutting tool is not able to cut out. Alternatives to cutting the hexagonal pocket such as electrical discharge machining (EDM) exist, however the CNC approach is more suitable for the cost-to-tolerance ratio and availability. The holes on the bars will house 4-40 setscrews to hold the specimen. The

CNC machine will provide close tolerances to accommodate up to 12 holes for setscrews and have enough spacing between them without weakening the integrity of the bars. In Figure 37 the tolerances and dimensions for the hexagonal pocket and set screw holes are shown.

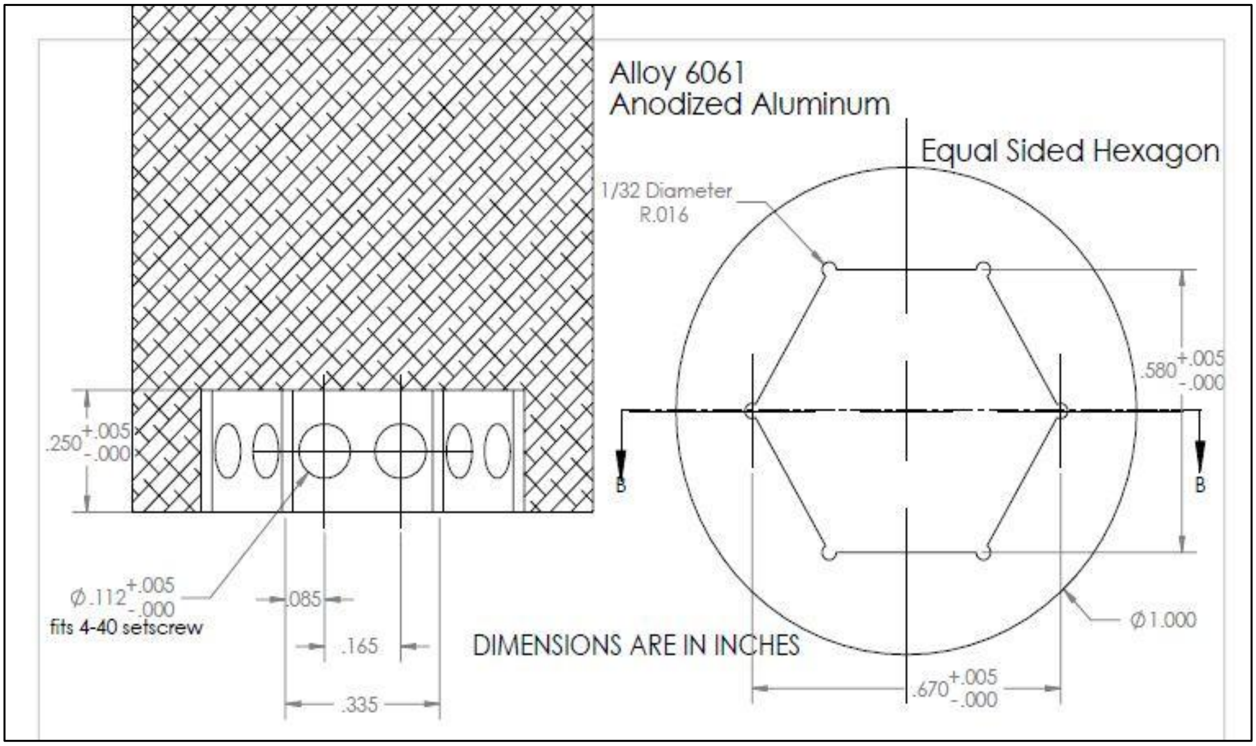


Figure 37 Hexagonal Pocket and Setscrews Dimensions with Tolerances

Safety Considerations

One is one too many. This statement denotes the importance of safety and striving for a zero incidence record. Due to this, certain safety considerations are taken into account when handling the equipment and the prototype. When testing, a protective clear shield is used to prevent pieces of shrapnel from reaching the person carrying out the experiment. The people present in the testing area must also wear protective eyewear. Additionally, due to the fact that the prototype is very heavy, special care is needed when moving it. If distances are longer than 3ft. a cart should be used to transport the prototype. When lifting it, the person responsible should square their bodies and bend their knees, lifting the weight with their legs and arms, rather than their backs.

Testing and Evaluation

The objective behind building a smaller and simplified version of the AFRL's Torsional Split Hopkinson Bar is to test various set screw configurations and conclude if the proposed design yields no anomaly in the results. In other words, it is desired to perform several tests and acquire data to provide accurate stress-strain diagrams that determine if there is relative motion in the specimen/bar interface. However, the prototype in question is not the same as the one used by the Air Force Research Lab, and certain modifications in the testing procedure take place. These alterations are needed since the model of the Kolsky bar is smaller, contains different components, the torque is applied manually with a torque wrench, and no clamp and pin mechanism is involved.

The experimental tests involve a torsional wave propagating through the incident bar, reaching the specimen and loading it with torque, and partially transmitting through the transmitter bar as well as partially reflecting back to the incident bar. In order to make this possible with accurate results, the prototype designed is scaled down considerably so as to reduce the amount of error. The source of error for the reduction in size is represented with the base, which would provide less stability than required if it were long. The prototype, which consists of a pair of aluminum bars, machined to have hexagonal pockets on one end of each bar, is aligned with each other by pillow blocks. These are attached to the firm and steady base with the pillow block set screws. It is important to specify that the transmitter bar is held fixed while the incident bar is allowed to rotate freely. This is considered to be another modification to the design of the Kolsky bar since the clamp and pin mechanism is not employed due to its complexity.

Testing Platform

The prototype is mounted on the steel structure, attached with pillow blocks. This holds the foundation of the testing platform. The reason the base is utilized is to provide stability because this method of testing is highly sensitive to motion. This is the complete purpose behind the optimization of the Torsional Split Hopkinson Bar of the AFRL.

A torque wrench is the means by which torque is applied to the system in the form of a shear pulse propagating through the model. The outside end of the incident bar contains a pocket that allows for the torque wrench to be introduced (Figure 30). Since it is a click type torque wrench, the desired torque is selected and applied. As soon as the torque is reached, the wrench "clicks".

Preparation for a torsional test with the prototype involves proper equipment mounting. The bars are lubricated to minimize friction between them and the pillow blocks. The bars are then placed within the pillow blocks and these are tightened in a crisscross manner to ensure equal distribution of tightening force. The last pillow block holding the end of the transmitter bar needs to be fully tightened to make that bar fixed while the incident bar is allowed to rotate freely. The specimen requires special care and attention since it is sensitive to motion during propagation of the shear stress pulse. The specimen needs to be centered in the hexagonal pocket by tightening the set screws in a crisscross manner as with the pillow blocks. This method is best since there are a large number of screws. Prior to beginning testing by applying torque to the incident bar, it is necessary to verify that the transmitter bar is actually fixed. This is accomplished by applying the desired amount of torque to the transmitter bar and observing there is no motion present.

The shear pulse that propagates through the bar is measured by strain gages connected in a full Wheatstone bridge circuit. The circuitry is modified by including an inverting operational amplifier (model: LM741 Operational Amplifier) that alters the power supply voltage output. This is needed because the output of strain gage bridges is relatively small. The result of employing an inverting op-amp is to increase the resolution of measurements and condition the signal of the circuit. The resistors used suffice a ratio A_v, which corresponds to the amplification of the signal coming from the strain gage bridge as seen in equation 12.

$$A_v = \frac{R_1}{R_2} = \frac{1000}{18} \qquad \text{Equation 27}$$

Another device utilized in the strain gage circuit was an RC low-pass filter with the purpose of reducing high-frequency noise thus obtaining a more uniform data [19]. The characteristics of the RC low-pass filter, for the resistor R_{LP} and the capacitor C_{LP}, are as follows,

$$R_{LP} = 100k\Omega \qquad\qquad C_{LP} = 0.1\mu F$$

By following equation 13, it is possible to determine the cutoff frequency ω_0 of the filter.

$$\omega_0 = \frac{1}{RC} = 100\, {}^{rad}/_{s} \qquad \text{Equation 28}$$

Similarly,

$$f_0 = \frac{\omega_0}{2\pi} = 15.9\ Hz \qquad \text{Equation 29}$$

This circuit is connected to a power supply to provide for the excitation voltage and the voltage for the op-amp. The circuit is also connected to an oscilloscope that allows the acquisition of experimental data with a visual representation of the test. The voltage output to the strain gages is adjusted to obtain adequate readings [2]. The oscilloscope model is TDS 2004B and its settings are summarized in table 7. Figure 38 is a schematic of the circuit built and Figure 39 represents the testing platform.

Table 13 Oscilloscope Testing Settings

Oscilloscope Testing Settings	
Record Length	2500 points
Sample Interval	0.001 s
Source	CH1 and CH2
Vertical Units	Volts
Vertical Scale	0.05
Vertical Offset	1.206
Horizontal Units	s
Horizontal Scale	0.25
Pt Fmt	Y
Probe Atten	10

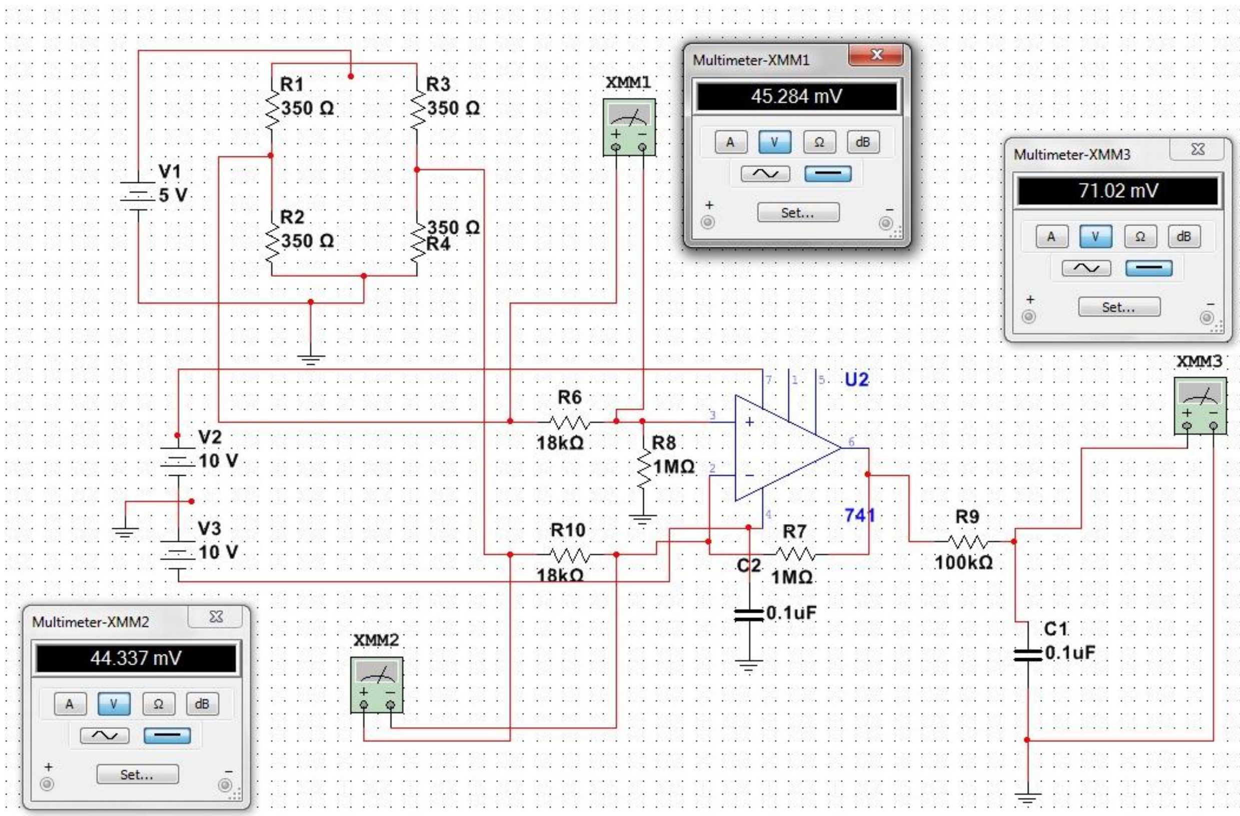


Figure 38 Circuit Diagram

The specimens used for testing are of the dimensions represented in Figure 18 (page 19). They are of two materials, Eglin base steel and 300m reinforced steel alloy. The first is a material developed by the AFRL and several of its properties are unavailable. Tables 14 and 15 represent the material properties of these two steels. Testing of the specimens was performed by applying 50 ft-lb of torque for both materials in all the configurations. This amount of torque was selected because the specimens have a maximum torque limit before fracture (Table 4) and this was enough to study the specimens in the elastic range. Additionally, the torque required to break from the static position was determined in order to examine the loss of torque due to friction. This value was obtained by applying a force with a spring whose constant was known and determining the spring's displacement. This value multiplied by the radius of the bar, yields the torque necessary to break the static position equal to 0.00377 ft-lb. This valued resulted so small, it was accounted as negligible and it was not necessary to recalculate the torque needed to be applied during testing. Equation 30 gives the relationship between the torque applied and the torque by friction.

$$\sum T_{Total} = T_{applied} - T_f = 0 \qquad \text{Equation 30}$$

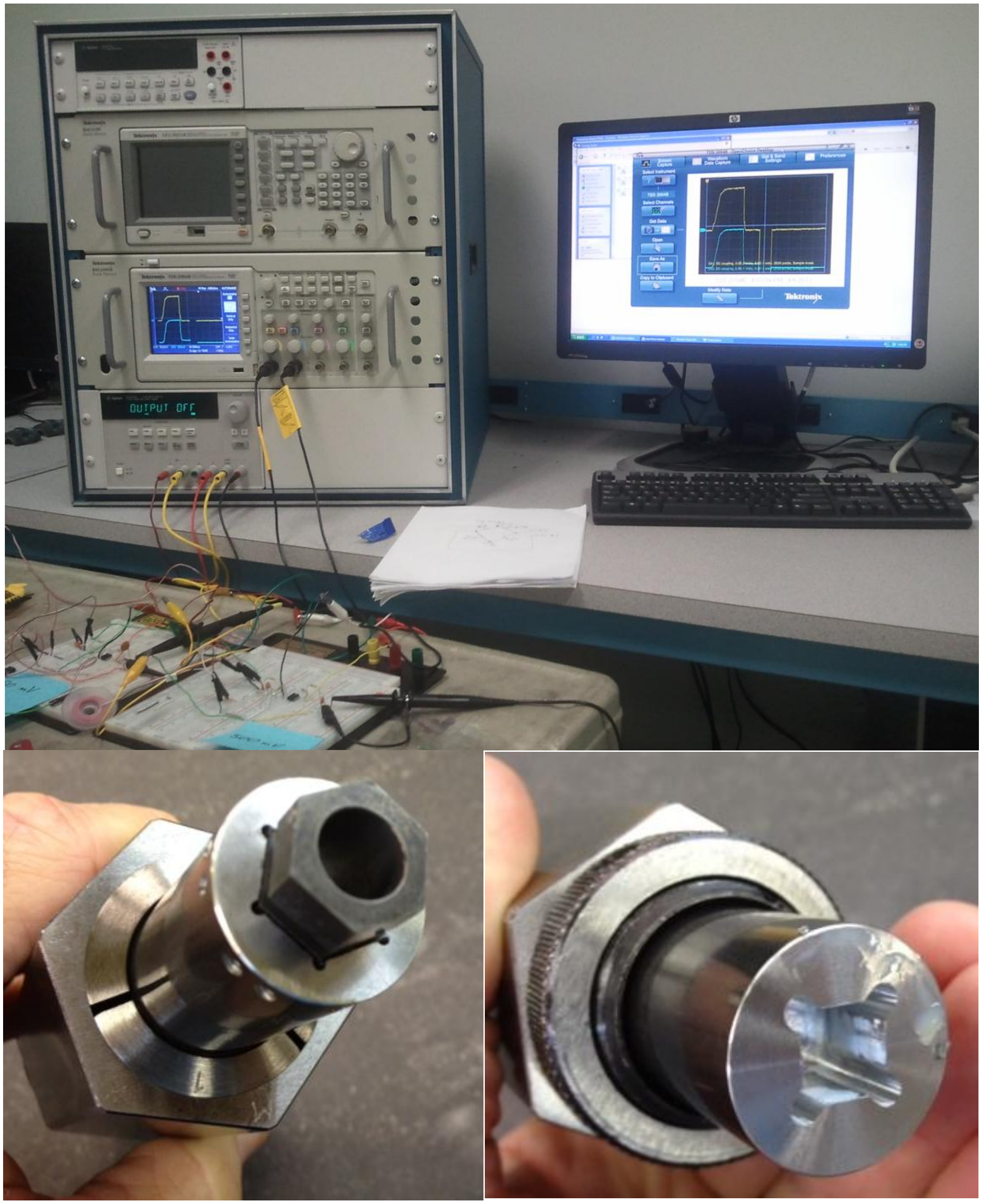


Figure 39 Testing Platform

Table 14 Properties of Eglin Base Steel

Eglin Steel		
Mechanical and Physical Properties	Ultimate Tensile Strength, psi	224,500
	Yield Strength, psi	263,700
	Rockwell Hardness	45.6
Chemistry	Iron	84.463-90%
	Carbon	0.16-0.35%
	Manganese	0.85%
	Silicon	max. 1.25%
	Chromium	max. 1.50-3.25%
	Molybdenum	max. 0.55%
	Nickel	5.00%
	Tungsten	0.70-3.25%
	Vanadium	0.05-0.3%
	Copper	0.50%
	Phosphorus	impurity, max. 0.015%
	Sulfur	impurity, max. 0.012%
	Calcium	max. 0.02%
	Nitrogen	impurity, max. 0.14%

Table 15 Properties of 300M Alloy Steel

300M Alloy Steel		
Physical and Mechanical Properties	Density, lb/cu. in.	0.283
	Ultimate Tensile Strength, psi	280,000
	Yield Strength, psi	230,000
	Rockwell Hardness	C55
	Shear Strength, psi	30,000
	Shear Modulus, Ksi	11,600
	Modulus of Elasticity, Ksi	29,700
	Elongation at Break	7%
	Poisson's Ratio	0.28
Chemistry	Carbon	0.38 - 0.46%
	Chromium	0.7 - 0.95%
	Iron	Balance
	Manganese	0.6 - 0.9%
	Molybdenum	0.3 - 0.65%
	Nickel	1.65 - 2%
	Phosphorus	max 0.01%
	Silicon	1.45 - 1.8%
	Sulphur	max 0.01%
	Vanadium	min 0.05%

Test Results and Data

The testing procedure involved using the same settings and parameters for all the configurations of set screws in order to establish a platform for comparison. The idea behind this is to prove that the configuration of 12 set screws is the best design since it reduces the most relative motion between the bar and specimen.

Figures 40-43 represent stress-strain diagrams for each of the four bar configurations after torsional tests were performed to the prototype. The curves are representative of experimental data in the form of time and voltage that has been analyzed following the equations in pages 21 and 22 to obtain shear strain and stress. The specimen materials used for 6, 8, 10, and 12 set screws are 300m steel and Eglin steel.

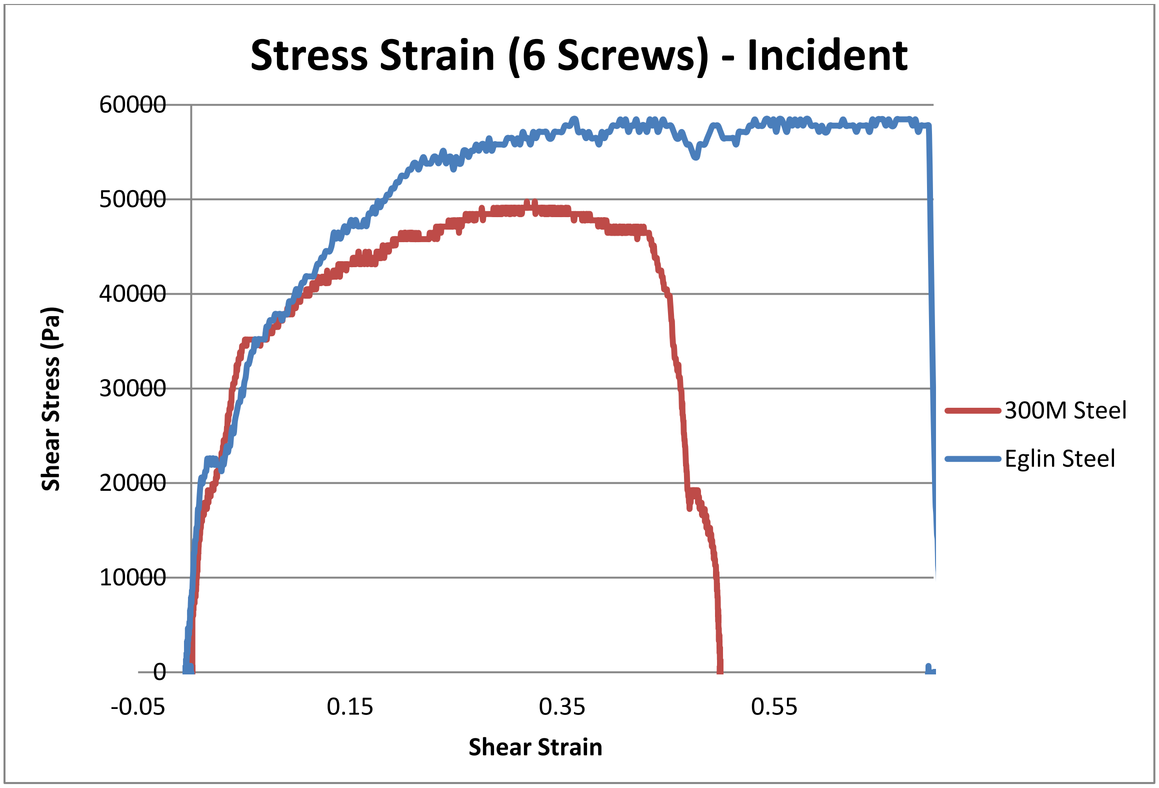


Figure 40 Shear Stress and Strain Diagram for 6 Set Screws

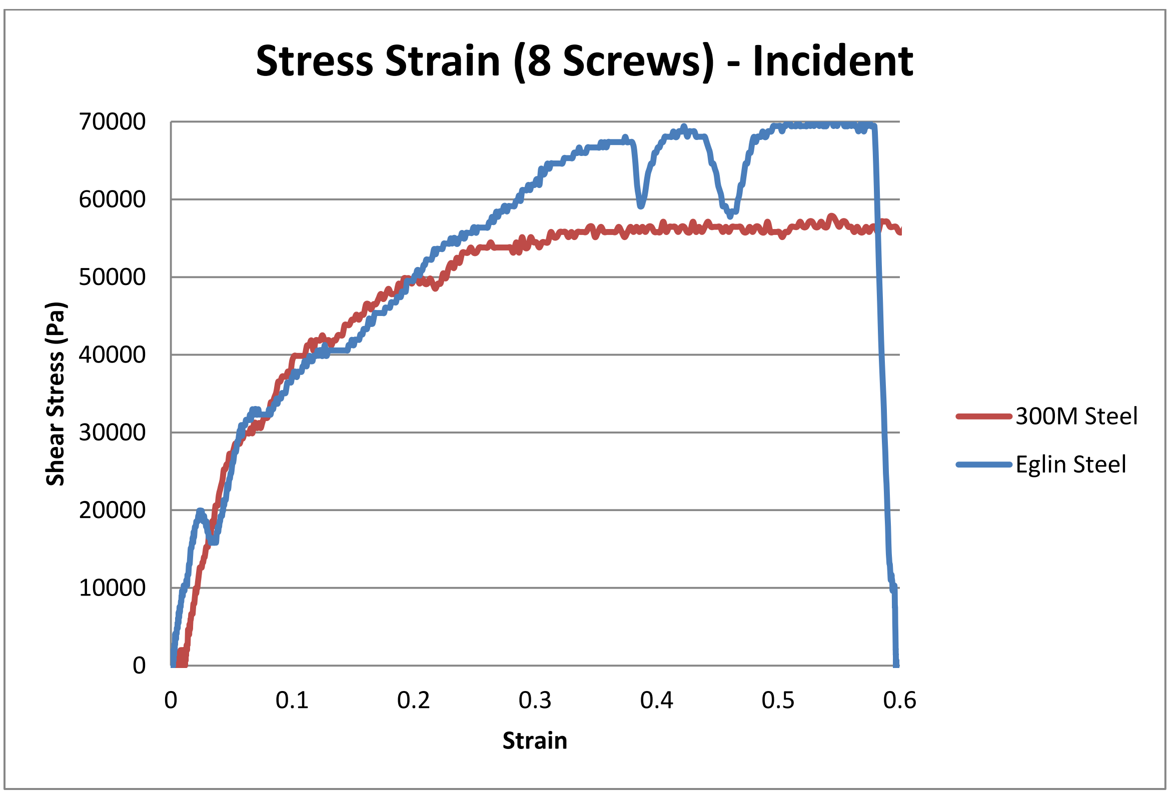


Figure 41 Shear Stress and Strain Diagram for 8 Set Screws

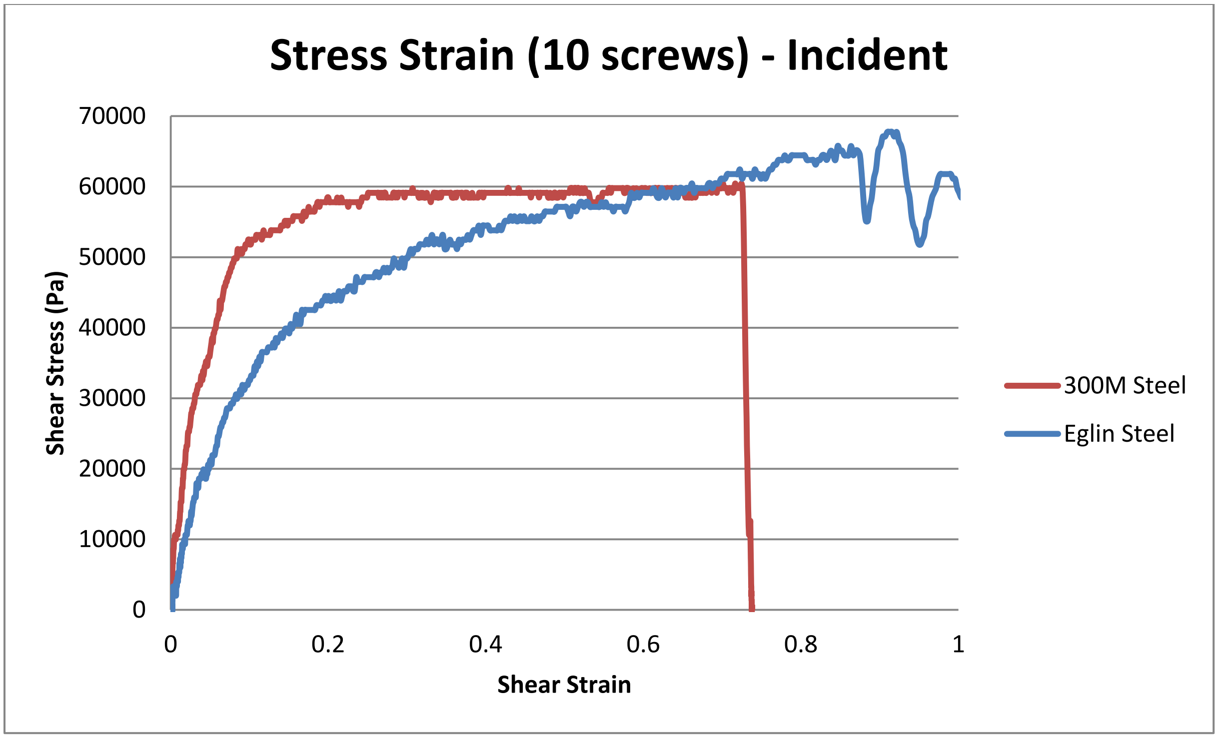


Figure 42 Shear Stress and Strain Diagram for 10 Set Screws

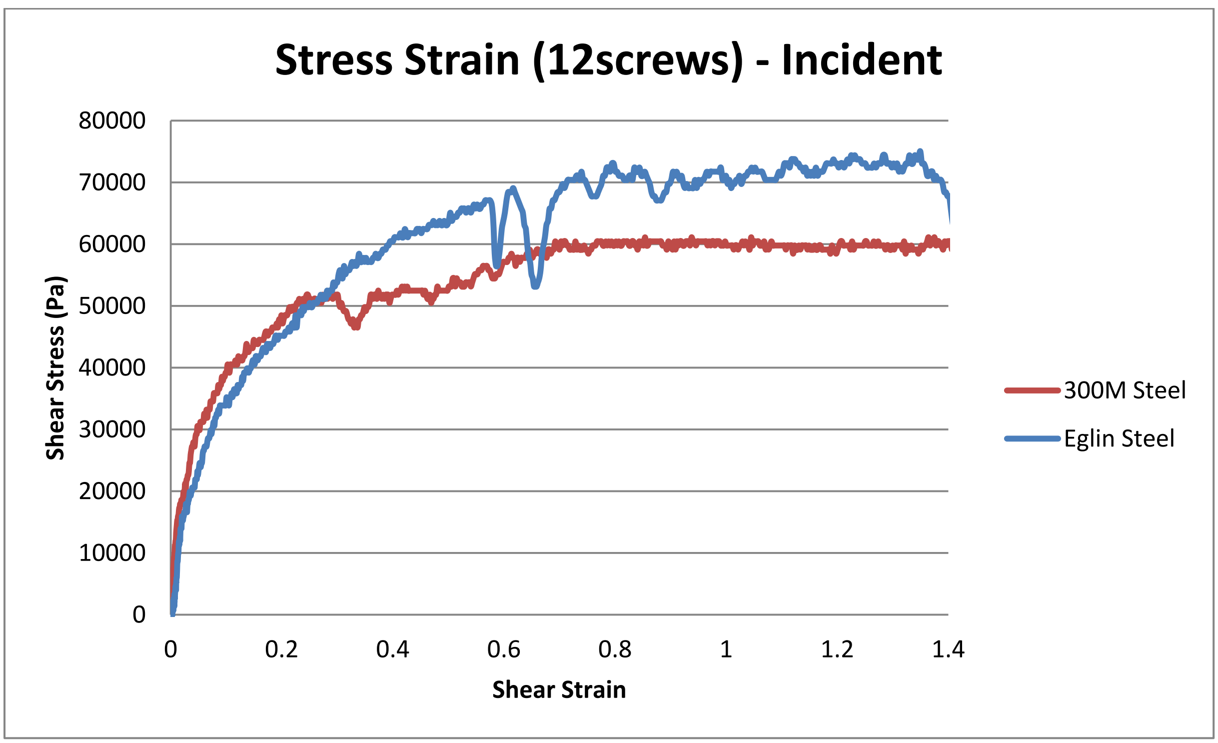


Figure 43 Shear Stress and Strain Diagram for 12 Set Screws

Evaluation of Experimental Results

The evaluation of the data acquired during testing takes place under certain considerations:

1. Analysis of elastic section of stress-strain diagrams since it is in this section that relative motion is known to take place.
2. Understanding the presence of noise in the signal due to the use of basic electric equipment and data acquisition system rather than a commercially built amplifier and filter configuration.
3. The difference between the AFRL and FIU's testing procedure and results. The results in this project are smaller (i.e. KPa rather than MPa).

The stress-strain diagrams include data from the point torque is initially applied until the failure of the specimen. In all cases, the specimen deformed considerably if not fractured. The diagrams represent the relationship between stress and strain, which is how the load applied deforms the specimen. The material characterizes each figure and its properties denote which regions will be present, such as elastic, plastic, and failure. The scope of these torsional tests focus on the elastic region, which is the stress the material can take without deforming when load is no longer applied.

Figures 40 and 41 exhibit a lack of uniformity in the elastic region, caused by relative motion present in the specimen/bar interface. The diagrams have uncharacteristic curves which are directly associated to anomaly in the results, and thus represent designs that do not work. Figure 42 represents the use of 10 set screws, and even though it looks less varying, anomaly is present in the form of small bumps in the elastic region. The stress-strain diagrams for 12 set screws (Figure 43) are the most uniform of all. This means that the proposed design is responsible for the most reduction of relative motion of the specimen in the hex pocket. The increase in set screws per face and overall use allow for more surface contact between the bar and the specimen, increasing the clutch and reducing movement during propagation of the shear pulse. Additionally, the use of 12 set screws, evens out the amount of torsional load on the set screws per face.

Improvement of the Design

The analysis of the test results allow to make corrections and recommendations for future work regarding the design of the bar. The following modifications are proposed:

1. Use a device that applies the torque to the bar in a uniform way.
2. Use of a clamp and pin mechanism, which allows for the torque to be released instantaneously.
3. Use a softer material for the prototype of the Kolsky bar in order to obtain better readings.

Cost Analysis

The expected cost for the project is broken down into the various parts and materials that are utilized to build the prototype and perform testing experiments.

Table 16 Purchase Order

Request for Purchase Order					
Item	Catalog No.	Description	Unit Cost	Qty.	Total
1	McMaster-CARR 5911k16	1" Dia, 6" long anodized aluminum shaft	$15.38	8	$123.04
2	McMaster-CARR 6359k37	Cast iron base-mounted babbitt-lined bearings	$53.96	5	$269.80
3	McMaster-CARR 94495A201	Flat point set screws, 4-40 (3/16")	$9.46	2	$18.92
4	McMaster-CARR 91251A620	Black-oxide alloy steel screws	$10.94	1	$10.94
5	McMaster-CARR 2662A13	Cobalt steel hand tap for mold steel	$14.28	2	$28.56
6	McMaster-CARR 85555A416	Torque wrench 3/8" drive	$191.20	1	$191.20
7	Micro- Meassurements CEA-06-187UV-350-P2	Shear/Torque pattern gages	$25.00	10	$250.00
8	Micro- Meassurements BAK-200	Instalation Kit	$88.20	1	$88.20
9	Engineering Manufacturing Center	Machining/ Lab	$210.00	1	$210.00
Grand Total:					$1,190.66

From Table 16, the various parts and materials mentioned in the section regarding the prototype and assembly can be found with their respective costs, manufacturers and/or suppliers. Cost decrease is seen by the reduction in scale of the incident and transmitter bars, whereas increased cost is manifested with the selection of shear/torque rosettes. Also, most of the parts are obtained through McMaster-Carr, a local supplier. The strain gages are purchased from Micro-Measurements. The manufacturing costs are also included and correspond to machining performed in the Florida International University. Refer to Appendix E for additional manufacturing cost information.

Global Learning

As part of the Global Learning Initiative, this Senior Design Project takes into consideration a diversity-oriented, multi-national, and realistic approach to further develop the notion of social responsibility through education and teamwork. The approach is based on focusing on specific tasks oriented towards making an impact in research communities worldwide.

The idea is focused on three notions:

1. Use of available resources to assure that others with the same or similar issues can use the materials employed for this project.
2. Practical resolution with an in-depth analysis to guarantee understanding of the design and testing applications utilized.
3. Publication of results so other laboratories worldwide can have access to them and learn from the tests carried out with the model of the Torsional Split Hopkinson Bar.

Another important aspect of the Global Learning initiative corresponds to what others have done to help and contribute in the development of this project. In order to carry out several tasks in the project timeline, advice and equipment were received from Professors and fellow students. An example of this instance is focused on the set-up for the electrical aspect of the project (circuitry). This is a case in which different engineering disciplines worked together for a common goal. This is present in everyday illustrations, because a project always includes more than one field.

Conclusions

The overall experience of working with a renowned institution such as the Air Force Research Lab has given rise to the opportunity of making an impact in a project used to generate significant results in research. The Torsional Split Hopkinson Bar has been established as an important piece of equipment due to its effect in Air Force and Military applications. With this bar, research entities such as the Air Force Research Lab are able to discover more information and properties regarding materials utilized in weaponry, equipment, and aircraft, between several others. These discoveries and further insight give foot to the improvement of current applications and the creation and development of new ones. The torsional Kolsky bar ultimately gives the AFRL the opportunities to do materials testing today so there are stronger, better, and faster applications tomorrow.

This Senior Design Group had the sole purpose of fixing the torsional Kolsky bar belonging to the AFRL in the Eglin Base. The problem originated in the section of the bar regarding the specimen and it involved relative motion between the bar and the specimen during high strain rate testing. This issue created anomaly in the data, which did not allow for successful testing of mechanical properties of materials and this in turn impeded the futuristic growth described above. The issue at hand was resolved by redesigning the specimen area using the proposed design of twelve set screws. This lead to the machining of a prototype with various set screw configurations, used to test various specimens and compare the results to establish the best relationship. The analysis described during the report is of structural and experimental nature, with which the acquired data from the strain gages is reduced to represent stress-strain graphs. The plots corresponding to the tests defined that relative motion is not present since they do not display anomalies corresponding to perceptible jumps of any nature.

The AFRL now receives a complete design of the specimen/bar interface with the purpose of developing a new set of bars with the design incorporated. This will eliminate the motion in the torsional Kolsky bar due to better surface contact and as a consequence accurate results when testing will be obtained.

Acknowledgements

We would like to thank the following people for helping us during this Senior Design Project. Your knowledge was invaluable and you helped us more than words can say.

Catherine Alviz, Victor Polanco, and Carlos Sousa for your resources and help with the electrical aspect of the project.

Dr. Wei Yu Bao for giving us advice with the strain gages.

Dr. Joel House and Erin Silva for answering our questions, funding our project, and guiding us in the right direction.

Dr. Sabri Tosunoglu for keeping us on task and having our best interest at heart.

Richard Zicarelli for machining our parts and giving us always the best advice for the construction of the prototype.

References

1. Gilat, A. (n.d.). Torsional kolsky bar Testing. *ASM Handbook Mechanical testing and Evaluation*, 505-515.

2. Weerasooriya, T. (1990). *The MTL Torsional Split-Hopkinson Bar.* US Army Materials Technology Laboratory.

3. Ramesh, K. T. (2008). High Strain Rate and Impact Experiments. *Springer Handbook of Experimental Solid Mechanics*, 1-26.

4. C. Y. Chiem, J. D. (1982). Strain Rate History Effects and Microstructural Aspects in Lithium Flouride and Aluminum Single Crystals After Dynamic Loading. *Rheologica Acta*, 413-415.

5. Flater, P. (2011). *Torsional Split Hopkisnon Bar Test Specimen.* Air Force Research Lab Munitions Directorate.

6. *Air Force Research Laboratory*. (2010). Retrieved from Eglin Air Force Base: http://www.eglin.af.mil/photos

7. *Air Force Research Laboratory.* (n.d.). Retrieved from XSS-10 Satellite for the Air Force Research Laboratory: http://www.af.mil/news/story.asp?id=123163537

8. House, J. W. (2011, October 15). Torsional Bar Architecture. Unpublished Internal Document.

9. *Curious Inventor.* (n.d.). Retrieved 02 2012, from Tutorial on Choosing Screw type, Size, Strength: http://store.curiousinventor.com/guides/Metal_Working/Screws/

10. *McMaster-Carr*. (n.d.). Retrieved from Flat Point Set Screws: http://www.mcmaster.com/#set-screws/=gc4ww5.

11. Pepi, M. S. (1997). *Examination of BSU-86/B Setscrews.* Army Research Laboratory.

12. *OnlineMetals.com*. (n.d.). Retrieved February 2012, from The OnlineMetals Guide to Aluminum: http://www.onlinemetals.com/aluminumguide.cfm

13. Lewis, J. L., & Campbell, J. D. (1972). *The Development and Use of a Torsional Hopkinson-Bar Apparatus*
14. Black, J. (2008). *Materials & Processes in Manufacturing*. (10 ed., p. 560,565,702,710). Hoboken, NJ: John Wiley & Sons, Inc.

15. Allen, M. (2011, April 25). Torque wrench 101. *Popular Mechanics*, Retrieved from http://www.popularmechanics.com/cars/how-to/repair/torque-wrench-101-how-to-get-the-right-amount-of-force
16. *Vishay Precision Group*. (n.d.). Retrieved from Micro-Measurements: http://www.vishaypg.com/micro-measurements/list/product-11244/
17. Gui-Tong, Y. (1985). The TSHP Technique for Materials Testing at High Rates of Strain. *Applied Mathematics and Mechanics, 6*(5), 393.
18. Acromag Incorporated. (2001). Introduction to strain & strain measurement. *Intelligent Strain Gauge Transmitter/Alarm*
19. Laboratory 3 strain gage sensors. In (2003). *Sensors and Actuators* Santa Barbara, Ca: University of California, Santa Barbara.

Appendix A Engineering Drawings

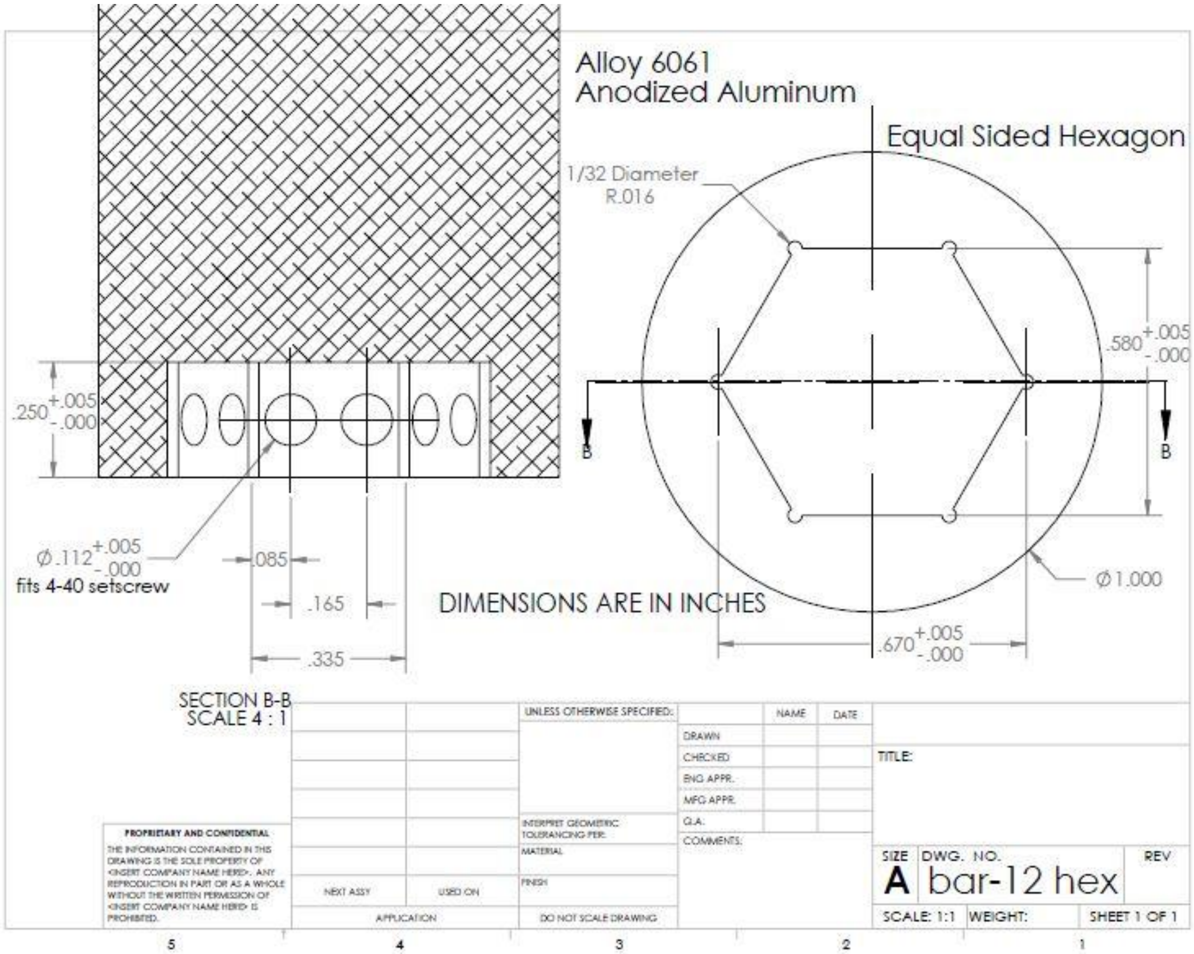


Figure 44 Hexagonal Socket Dimensions with 12 hole configuration

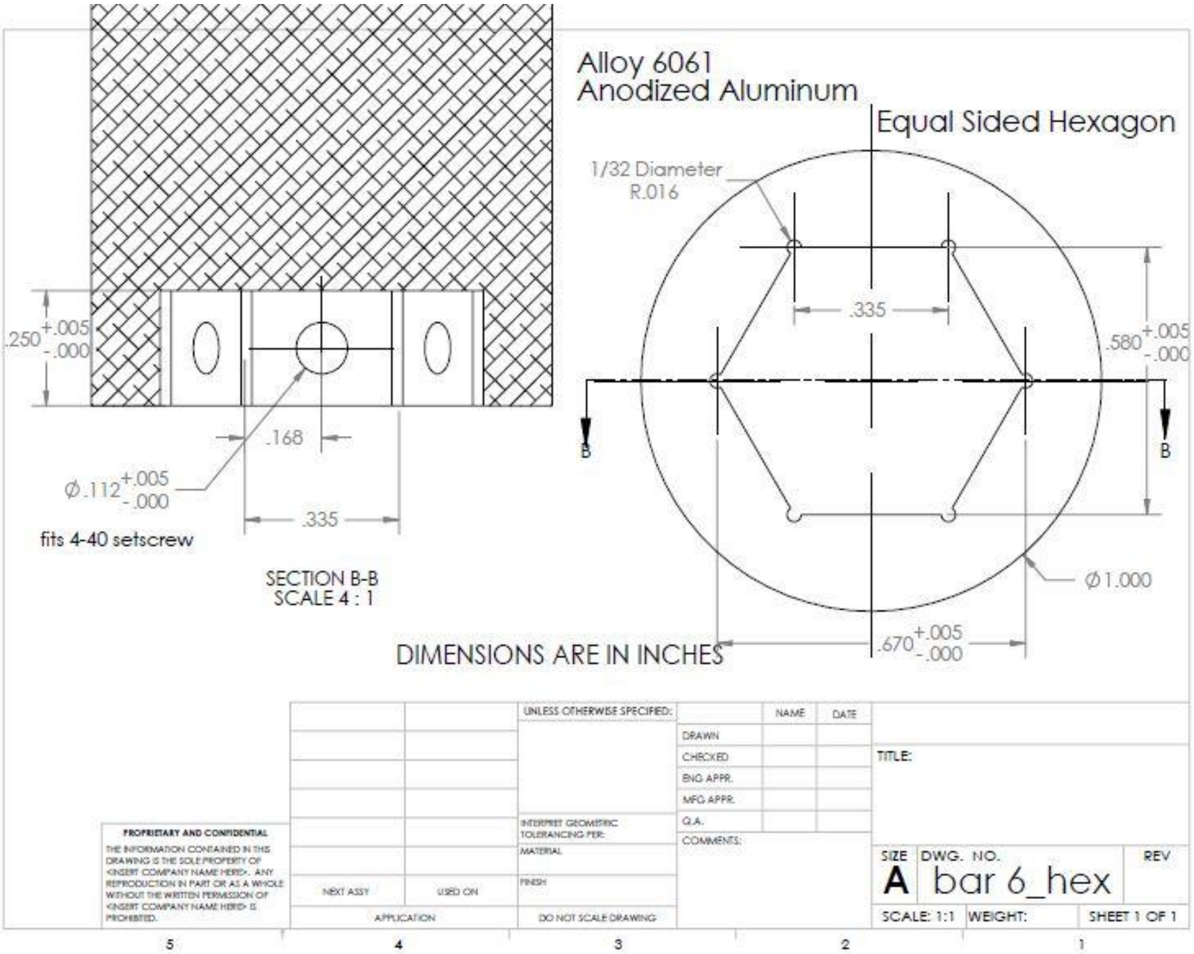


Figure 45 Hexagonal Socket Dimensions with 6 hole configuration

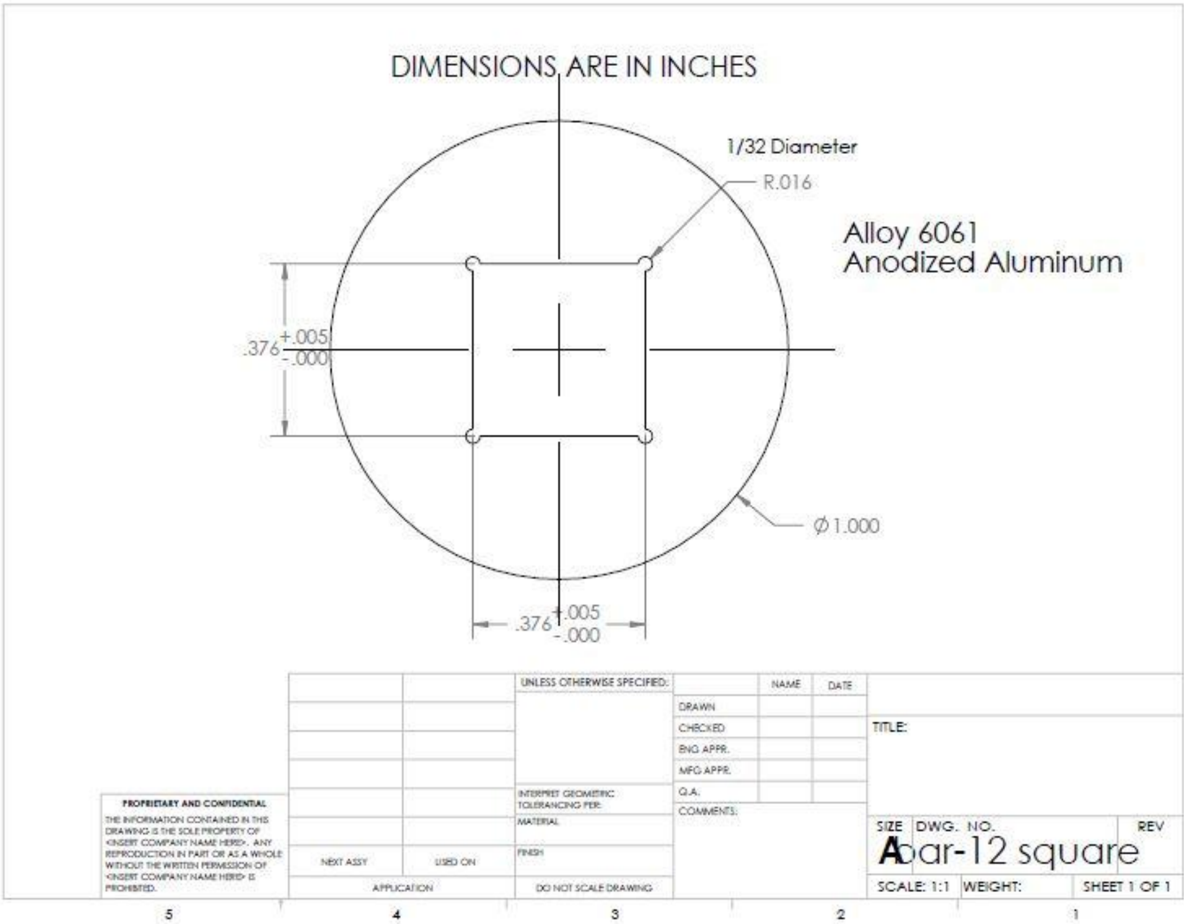


Figure 46 Square socket Dimensions for both bars (where torque wrench is attached)

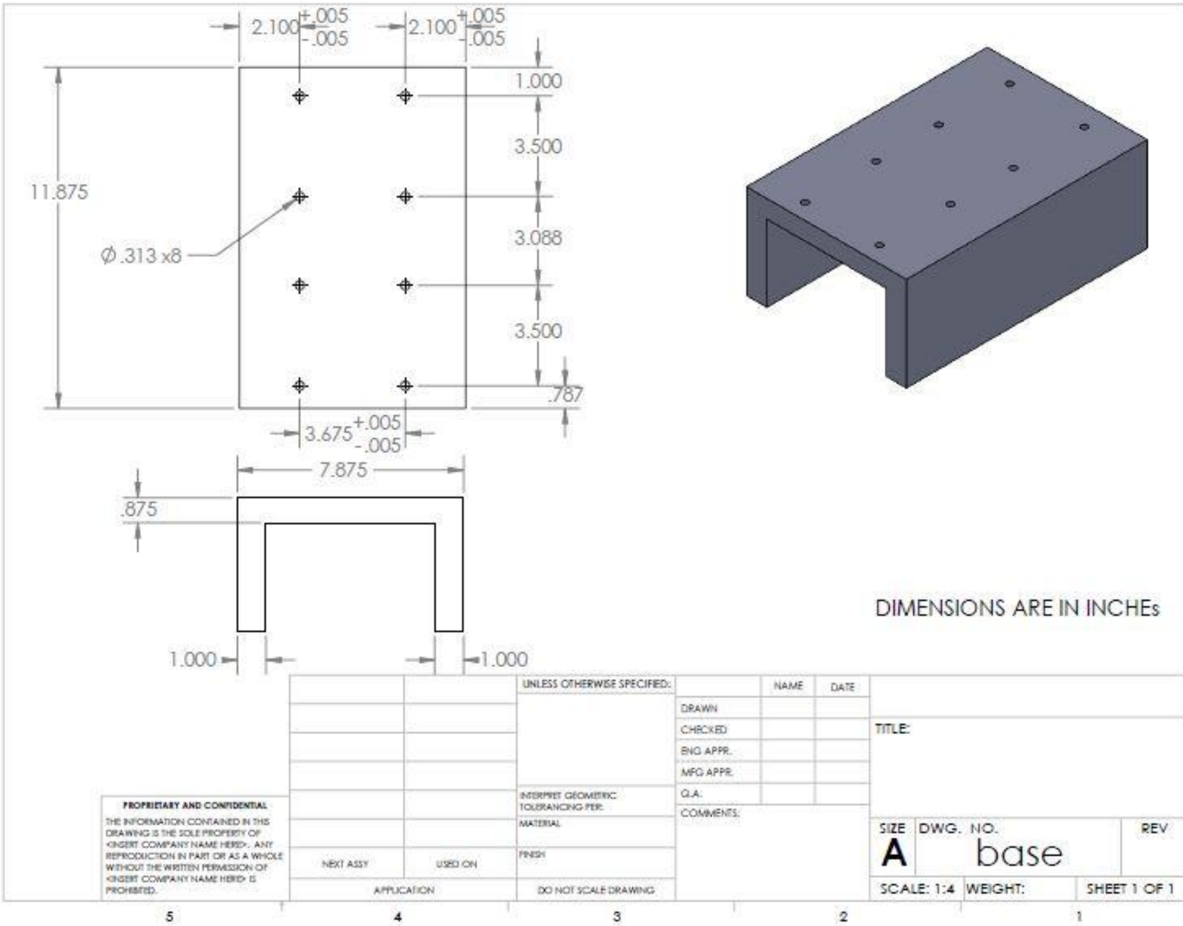


Figure 47 Technical Drawing for the Base

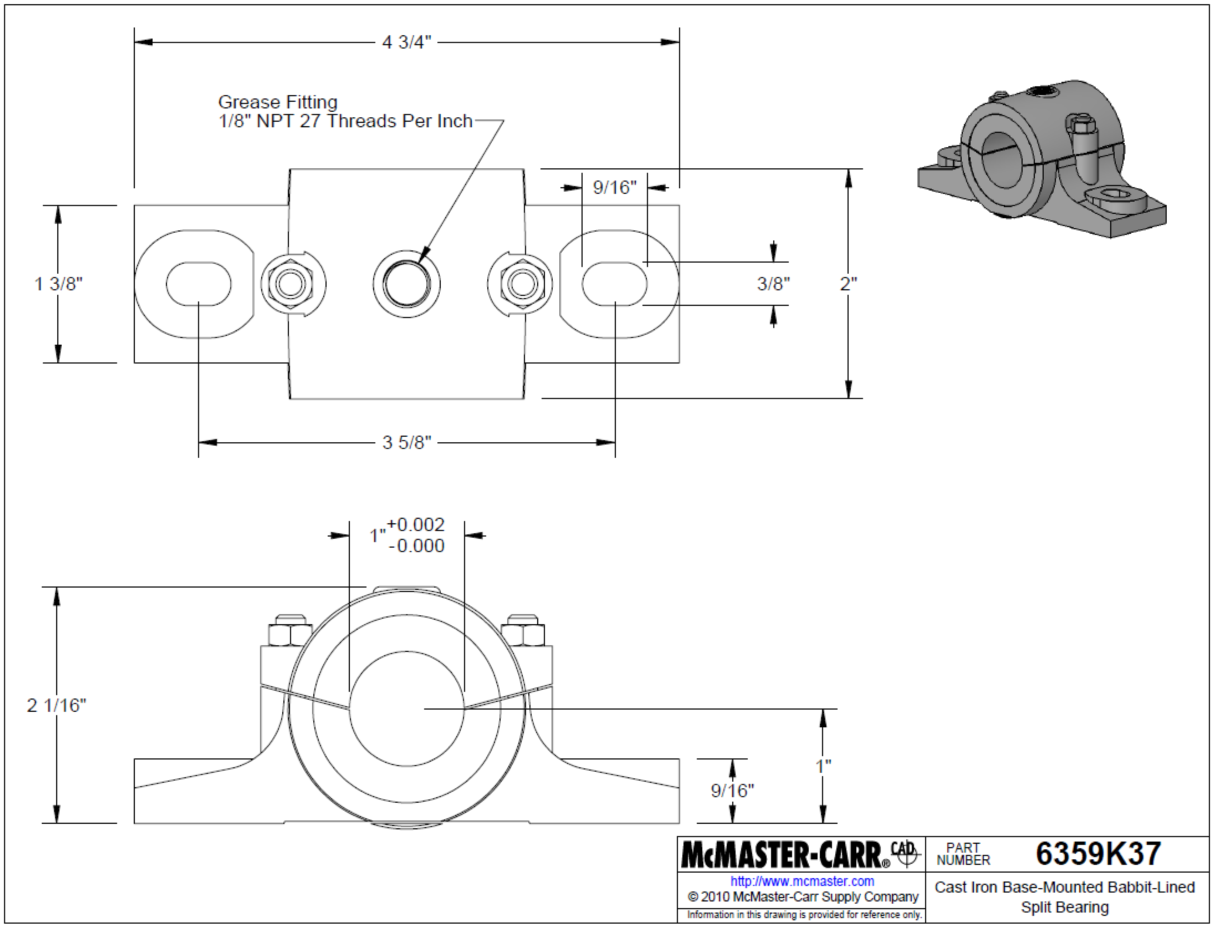


Figure 48 Technical Drawing for Pillow Blocks [10]

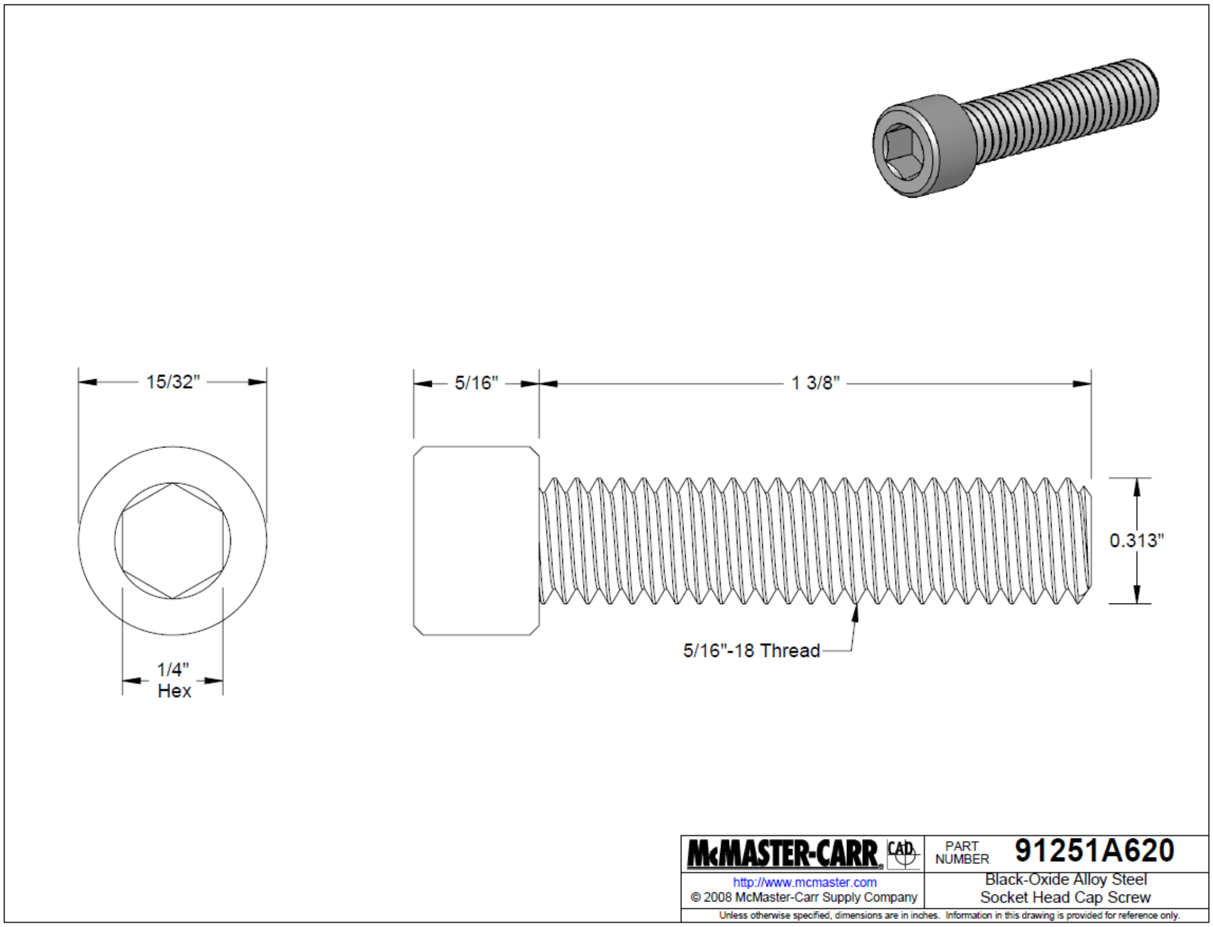


Figure 49 Technical Drawings for Bolts [10]

Appendix B Parts Information

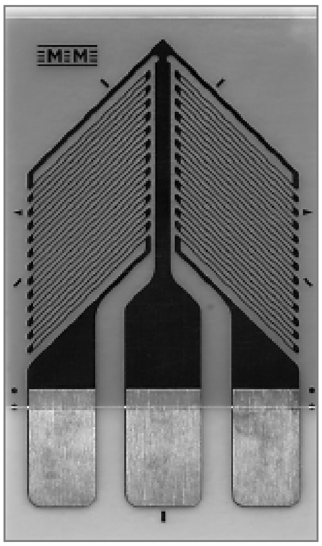
187UV

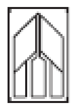
Micro-Measurements

VISHAY PRECISION GROUP

General Purpose Strain Gages - Shear/Torque Pattern

GAGE PATTERN DATA





actual size

GAGE DESIGNATION See Note 1	RESISTANCE (OHMS)	OPTIONS AVAILABLE See Note 2
CEA-XX-187UV-120	120 ± 0.4%	**P2**
CEA-XX-187UV-350	350 ± 0.4%	**P2**

DESCRIPTION

Two-element 90° rosette for torque and shear-strain measurement. Sections have a common electrical connection. Exposed solder tab area is 0.13 x 0.08 in [3.3 x 2.0 mm].

GAGE DIMENSIONS — Legend: ES = Each Section; S = Section (S1 = Sec 1); CP = Complete Pattern; M = Matrix; inch / millimeter

Gage Length	Overall Length	Grid Width	Overall Width	Matrix Length	Matrix Width
0.187 ES	0.560 CP	0.150 ES	0.320 CP	0.63	0.39
4.75 ES	14.22 CP	3.81 ES	8.13 CP	15.9	9.8

GAGE SERIES DATA See Gage Series data sheet for complete specifications.

Series	Description	Strain Range	Temperature Range
CEA	Universal general-purpose strain gages.	±5%	−100° to +350°F [−75° to +175°C]

Note 1: Insert desired S-T-C number in spaces marked XX.

Note 2: Products with designations and options shown in bold are not RoHS compliant.

www.micro-measurements.com For technical questions, contact: micro-measurements@vishaypg.com Document Number: 11244
108 Revision: 02-Feb-10

Figure 50 Specifications for Shear/Torque Pattern Strain Gage [16]

Appendix C Simulation Results

Twelve Set Screws

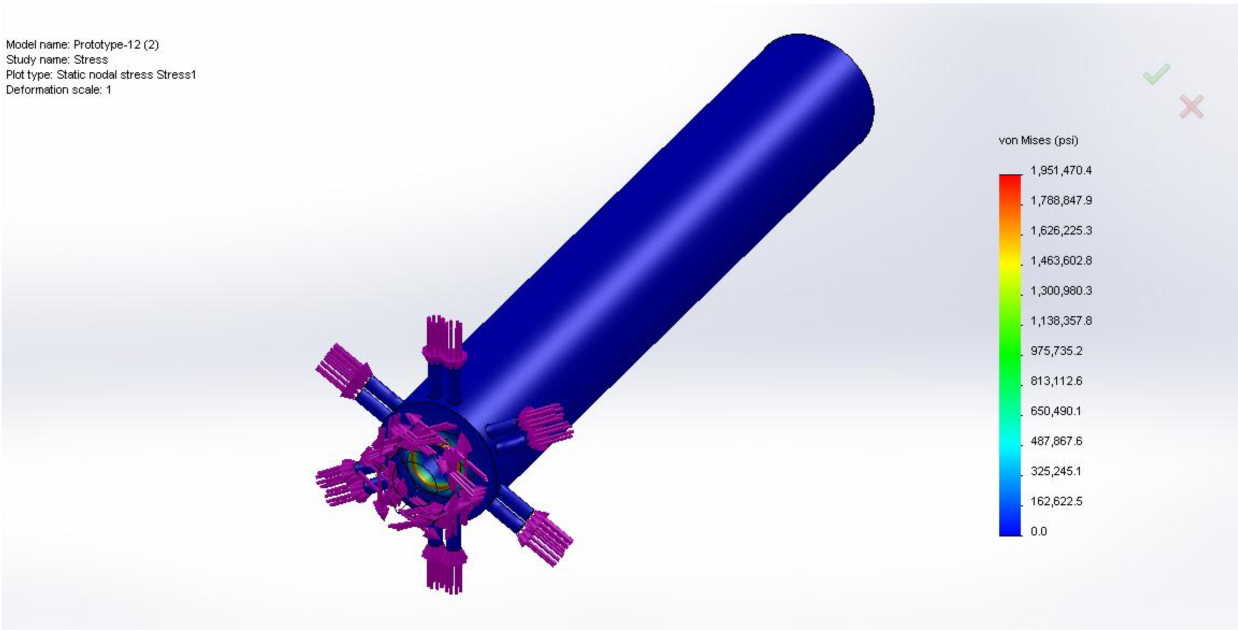


Figure 51 Displacement Study for 12 Set Screws - Isometric View

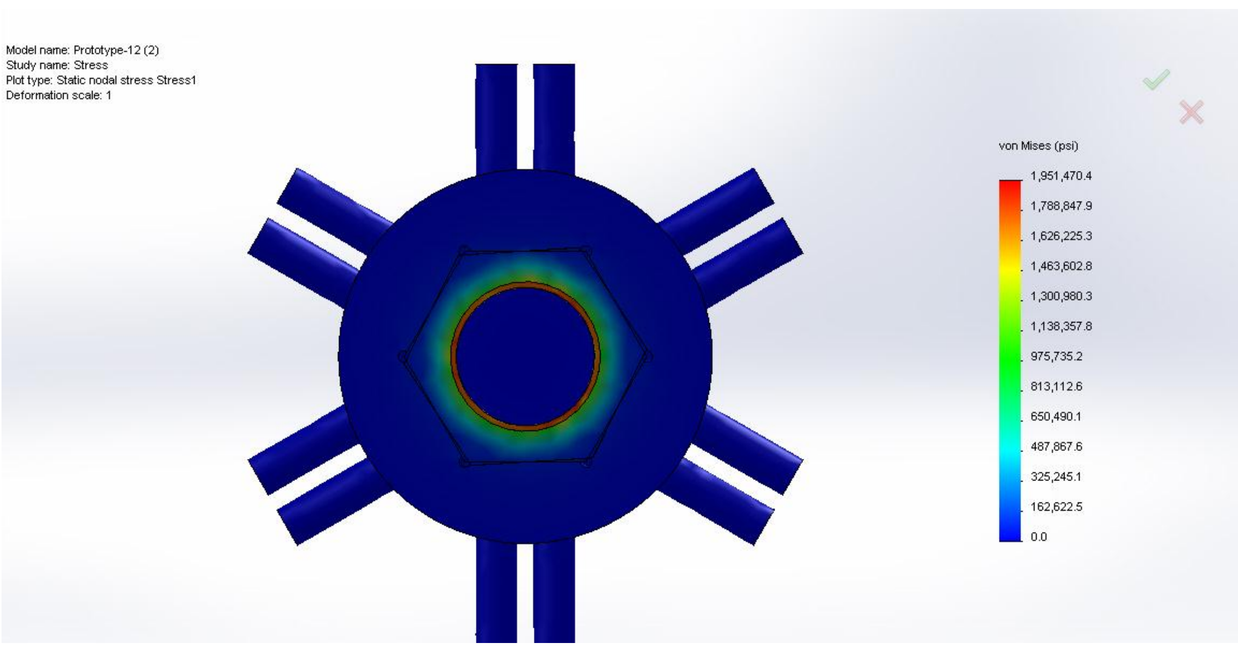


Figure 52 Von Mises Stress Study for 12 Set Screws - Front View

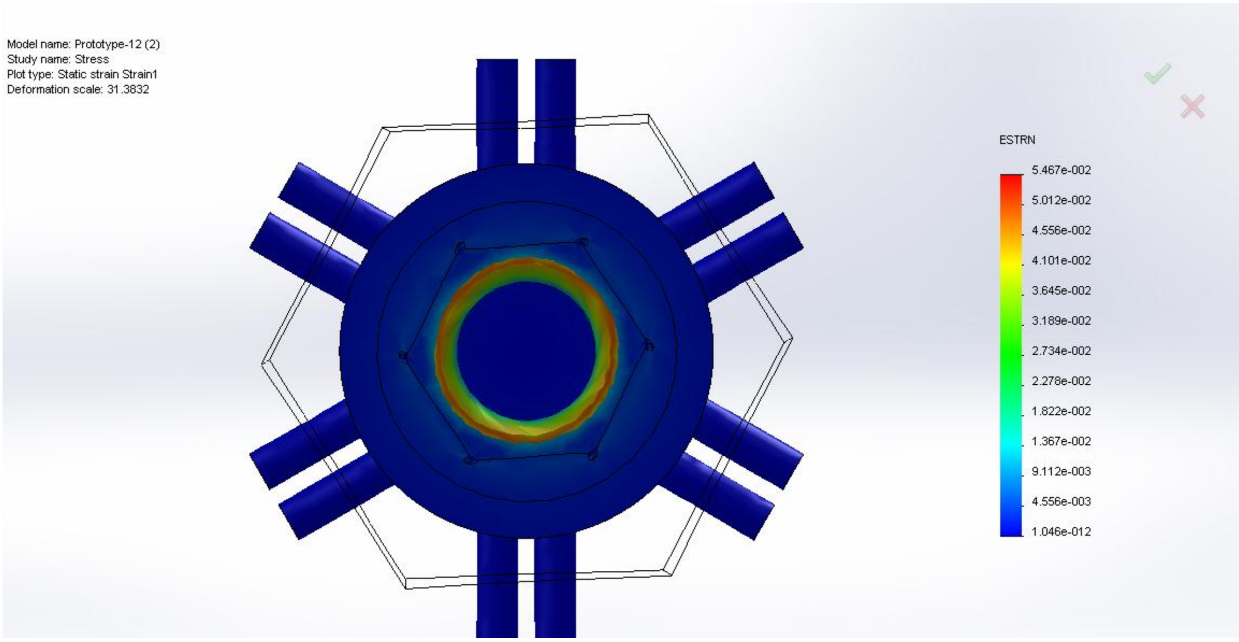


Figure 53 Strain Study for 12 Set Screws - Front View

Ten Set Screws

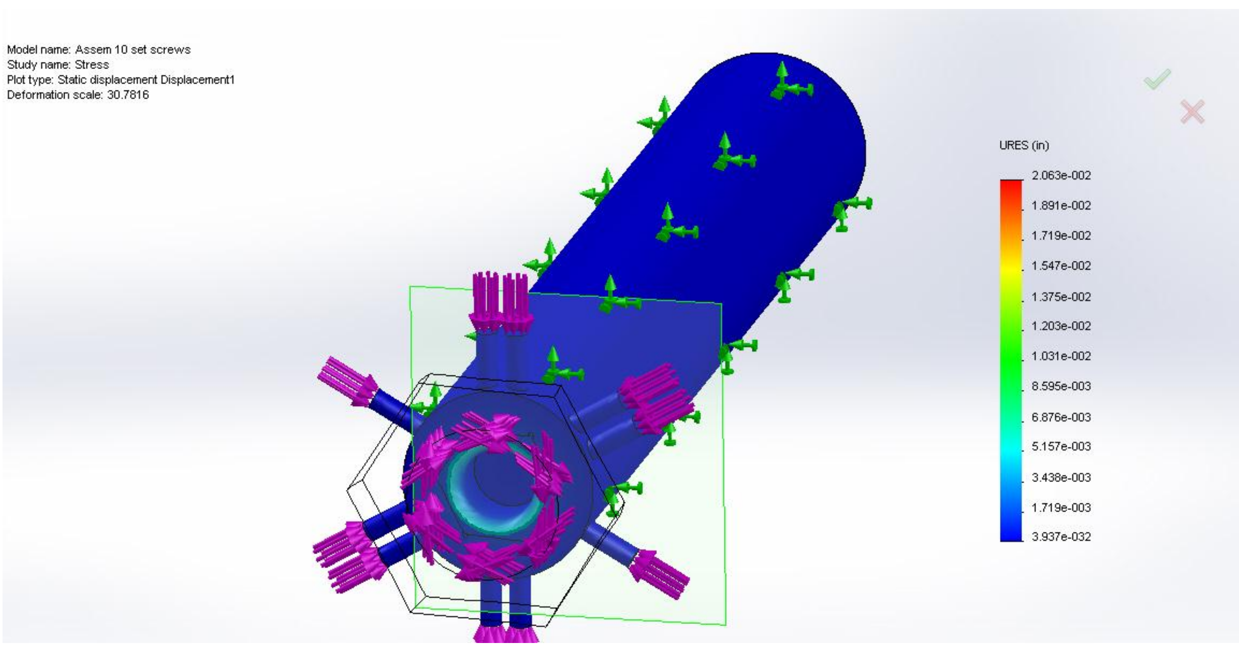


Figure 54 Displacement Study for 10 Set Screws - Isometric View

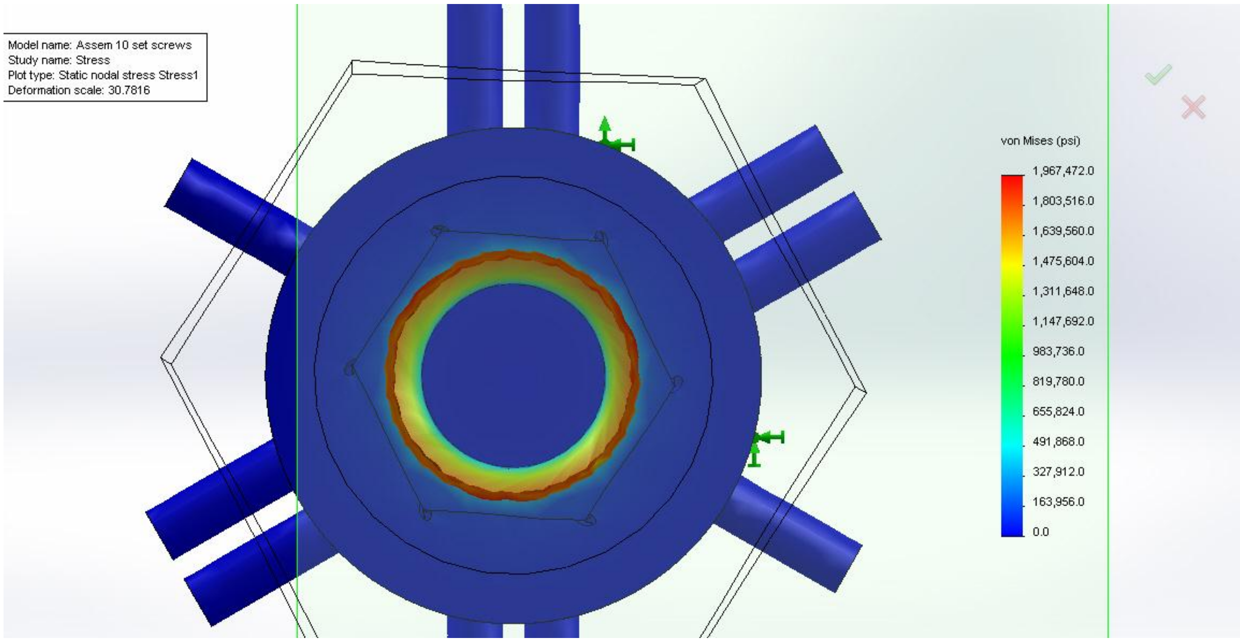


Figure 55 Von Mises Stress Study for 10 Set Screws - Front View

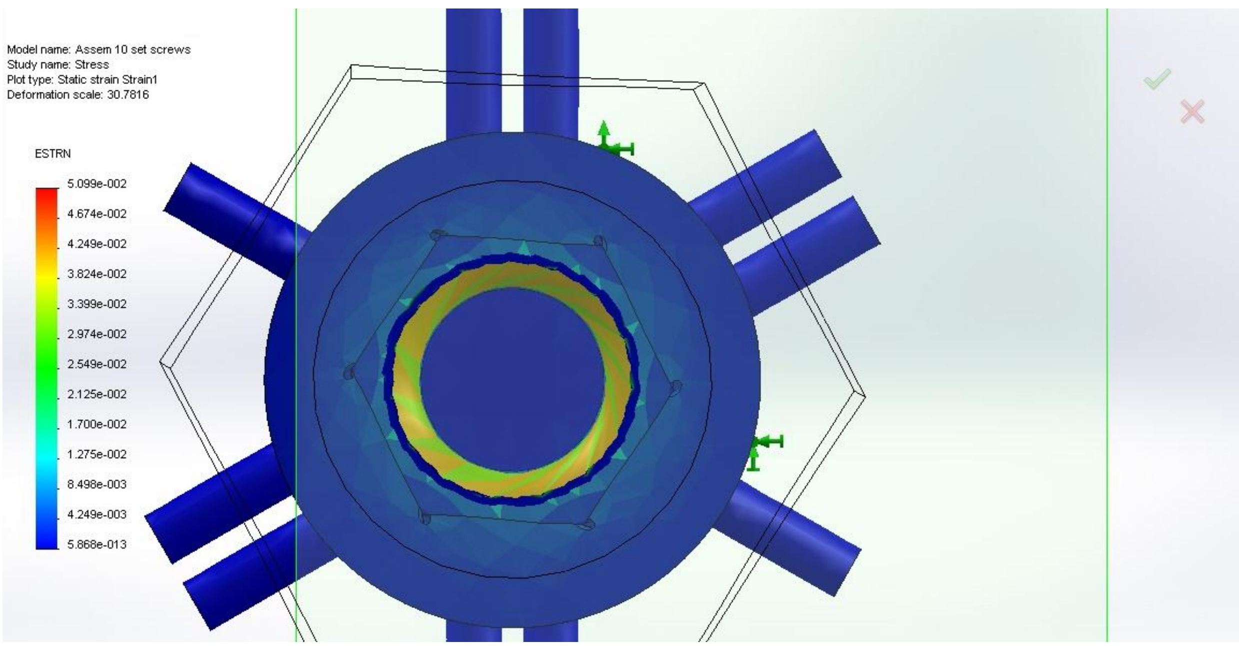


Figure 56 Strain Stress Study for 10 Set Screws - Front View

Eight Set Screws

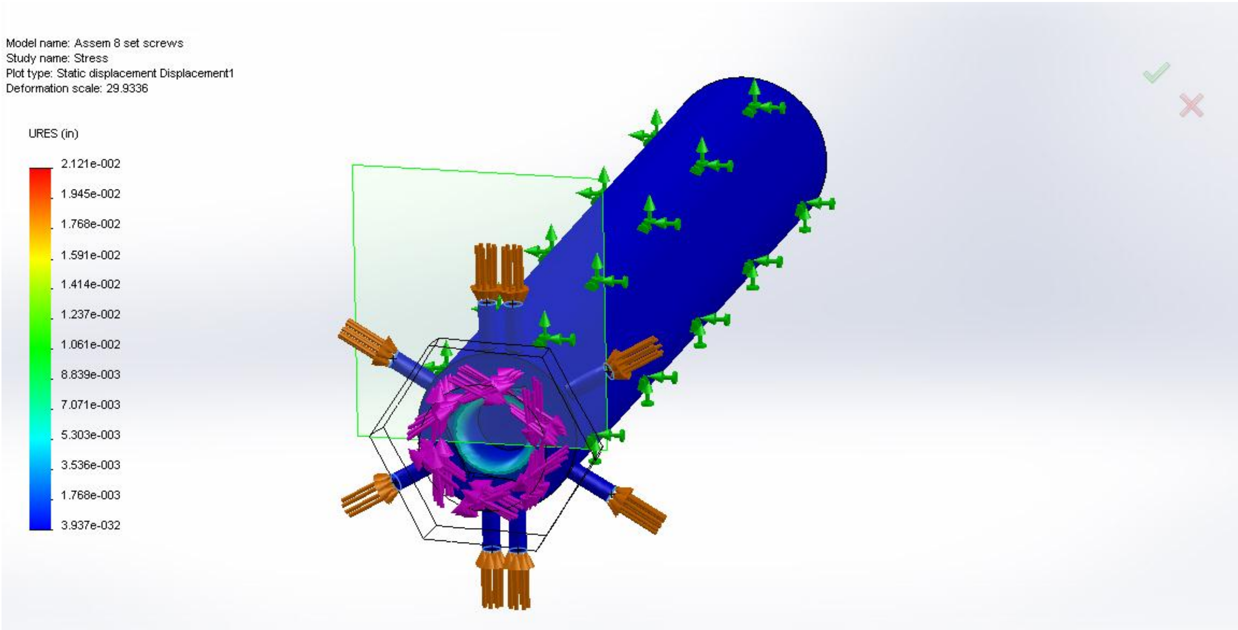


Figure 57 Displacement Study for 8 Set Screws - Isometric View

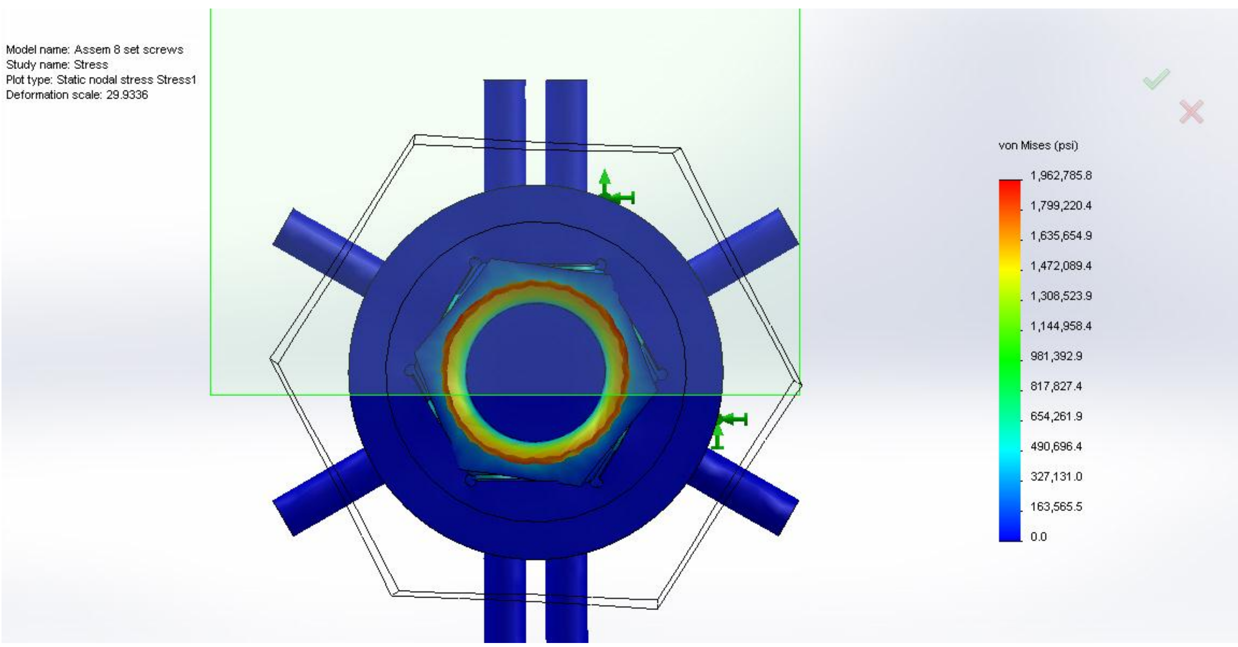


Figure 58 Von Mises Stress Study for 8 Set Screws - Front View

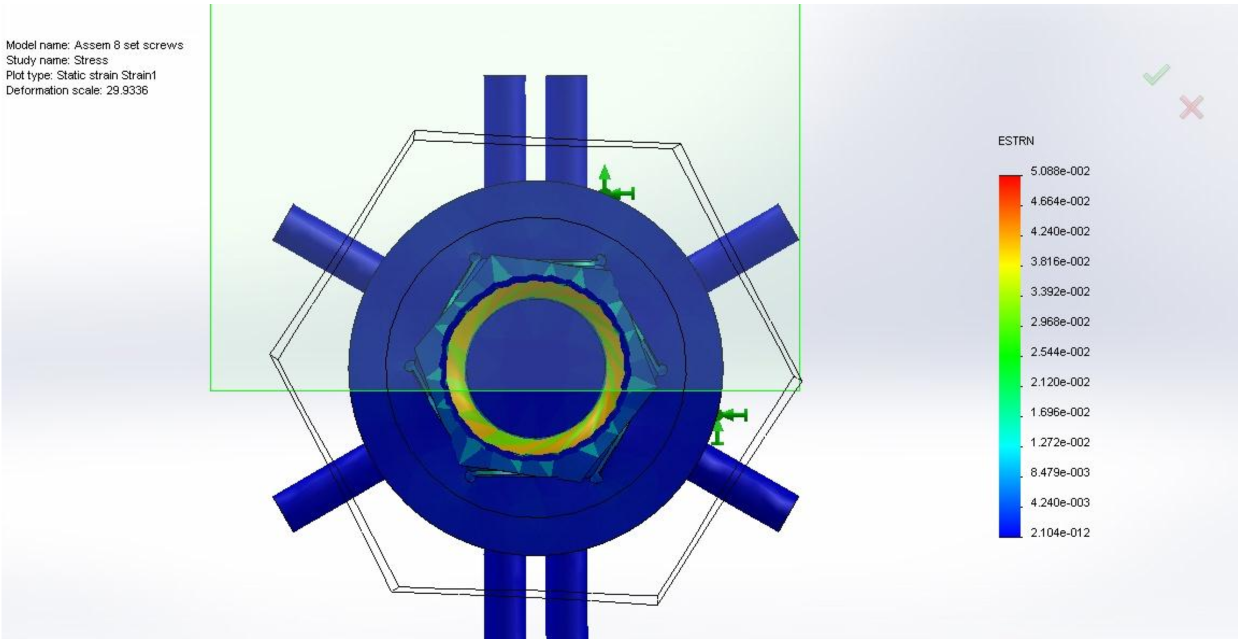


Figure 59 Strain Study for 10 Set Screws - Front View

Six Set Screws

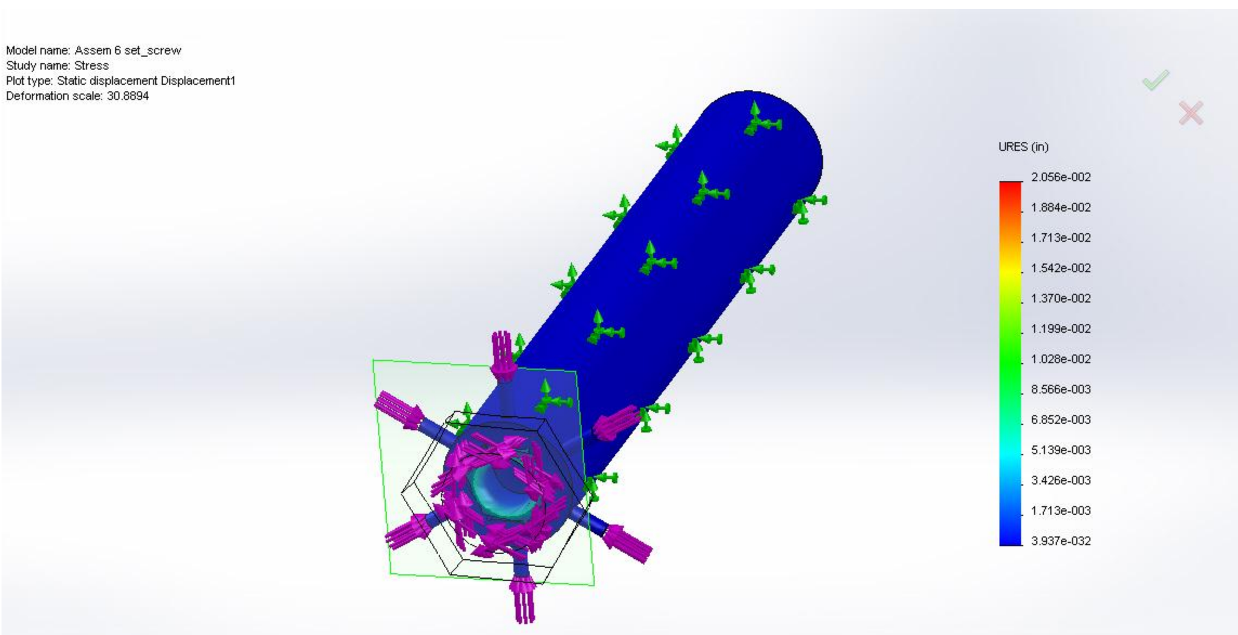


Figure 60 Displacement Study for 6 Set Screws - Isometric View

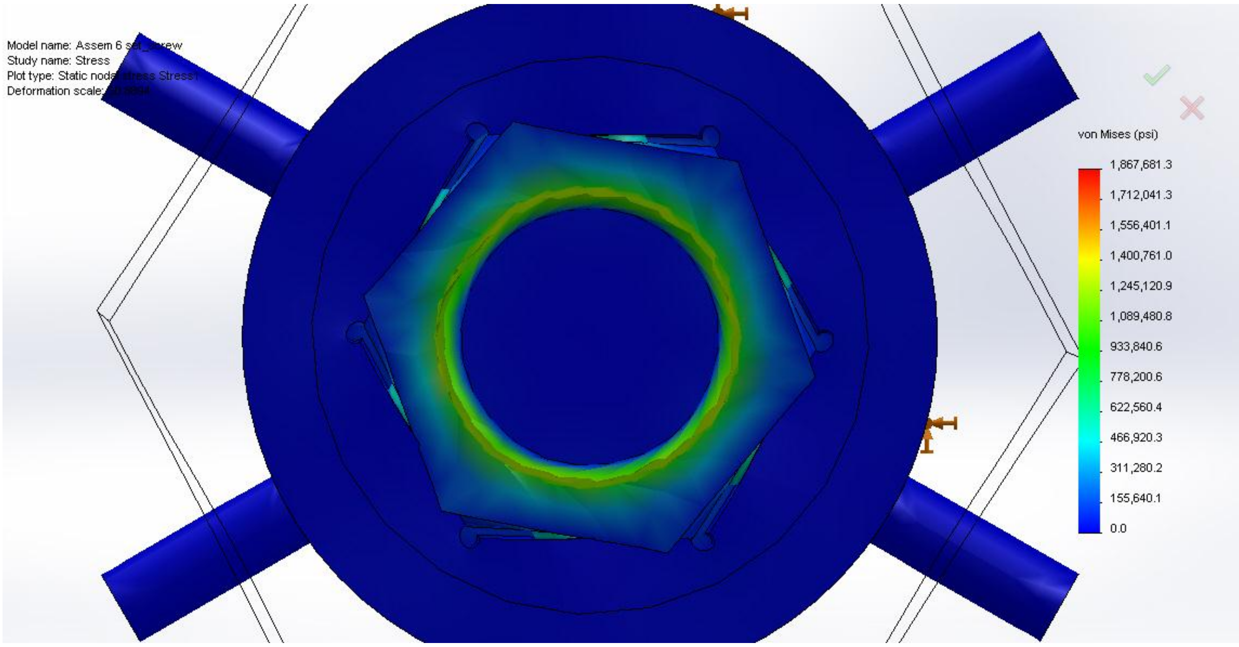


Figure 61 Von Mises Stress Study for 6 Set Screws - Front View

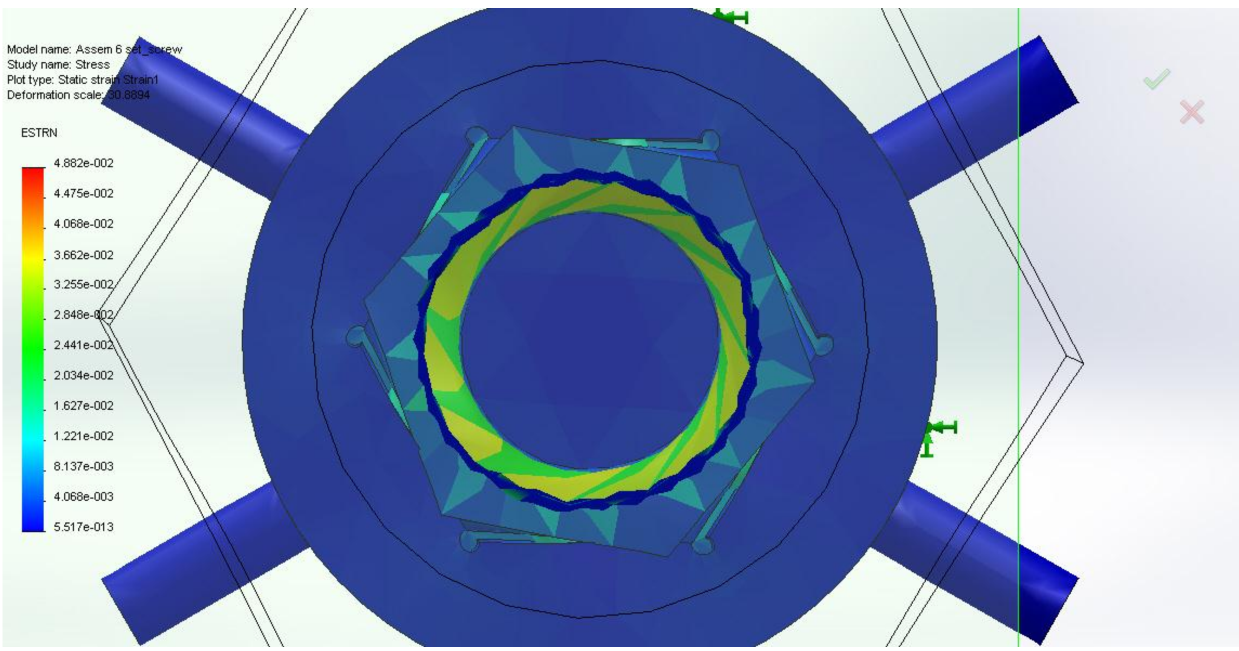


Figure 62 Strain Study for 6 Set Screws - Front View

Set Screws

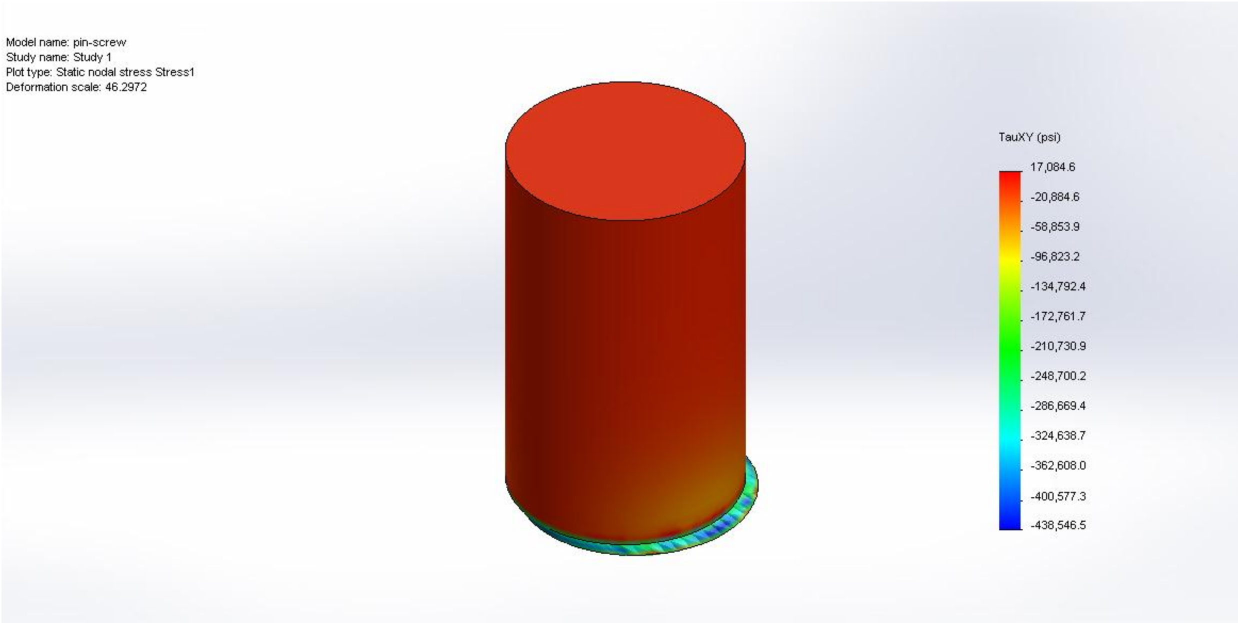


Figure 63 Shear Stress Study for Set Screw

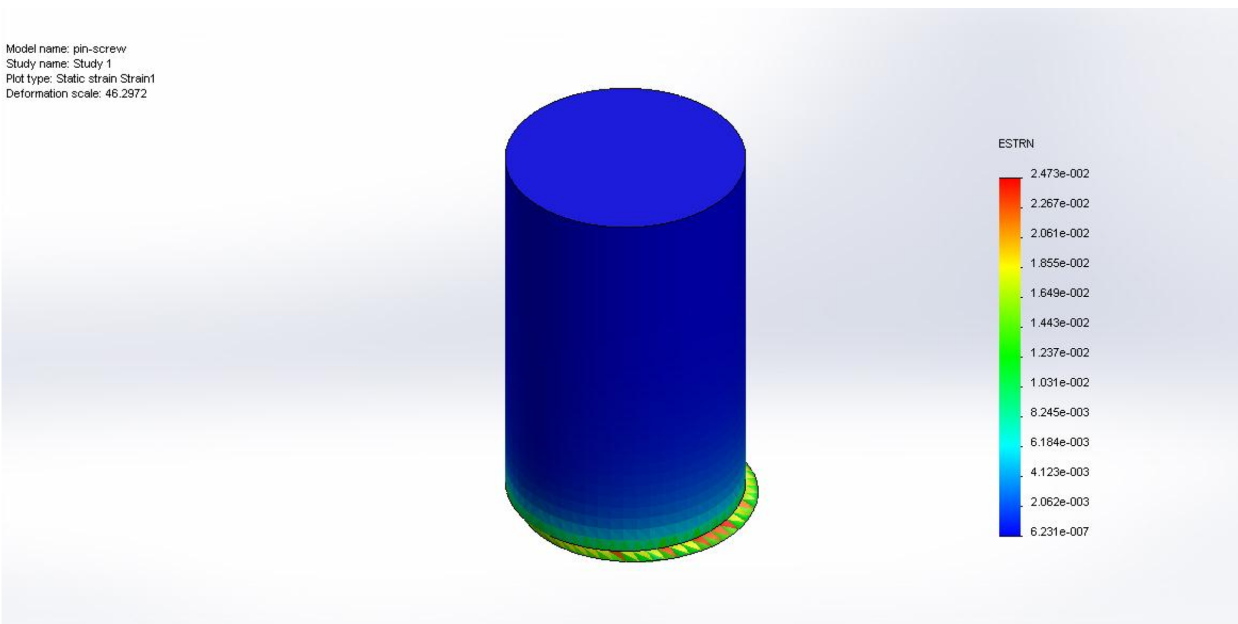


Figure 64 Equivalent Strain Study for Set Screw

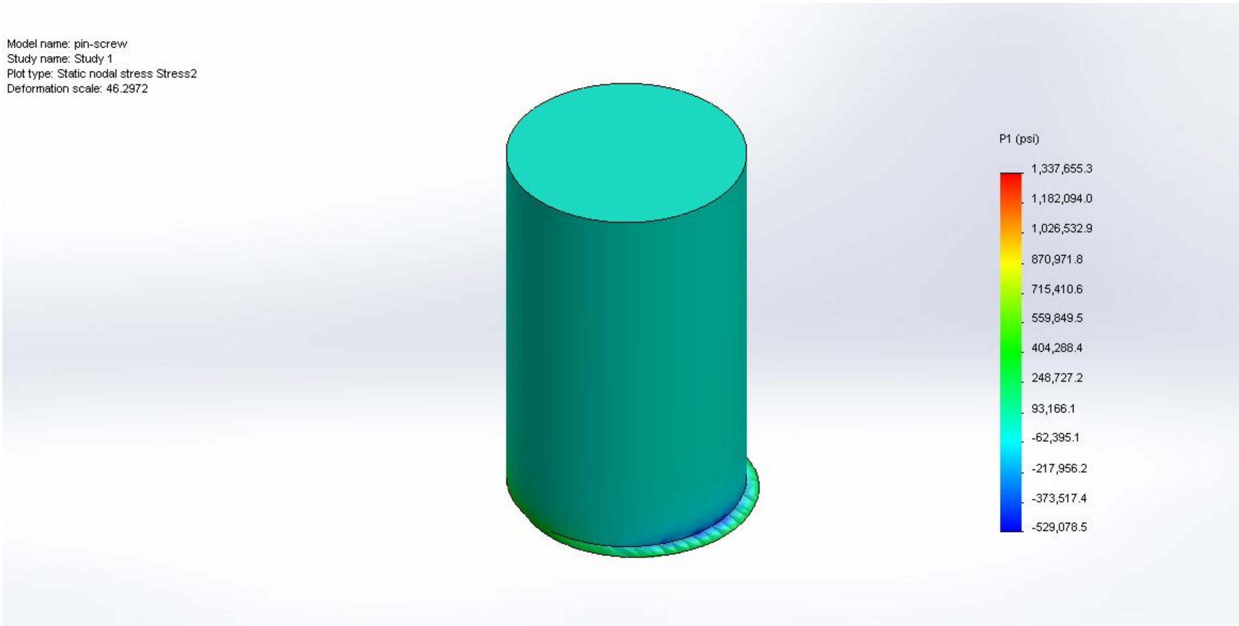


Figure 65 Principal Stress for Set Screw

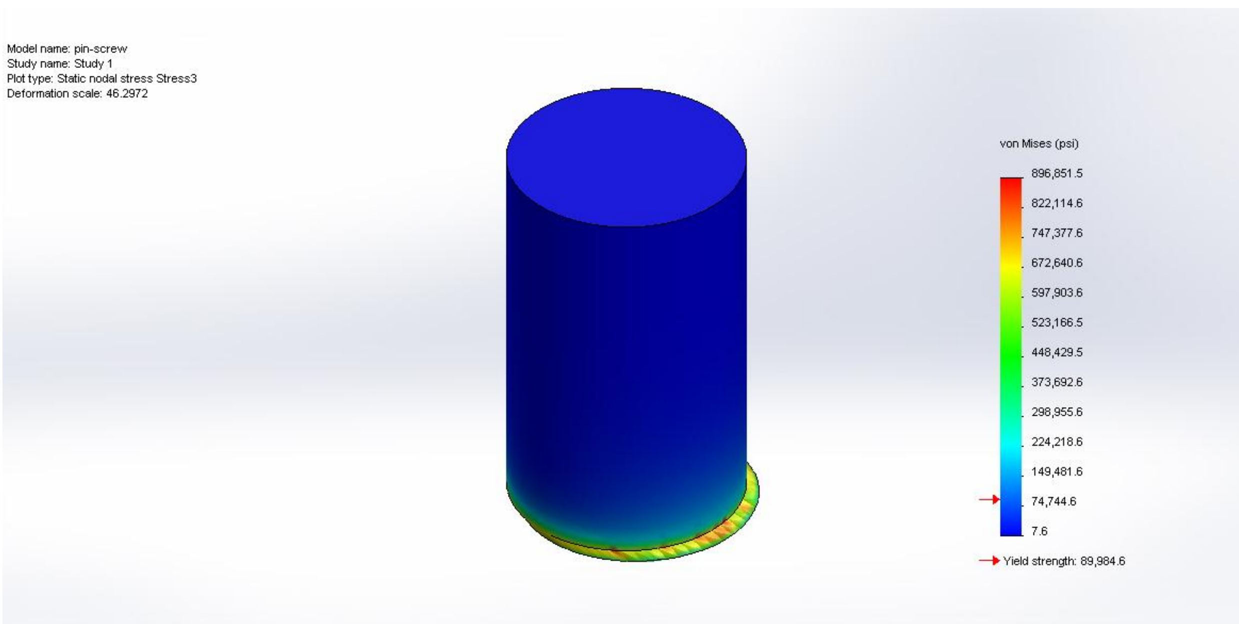


Figure 66 Von Mises Stress Study for Set Screw

Specimen

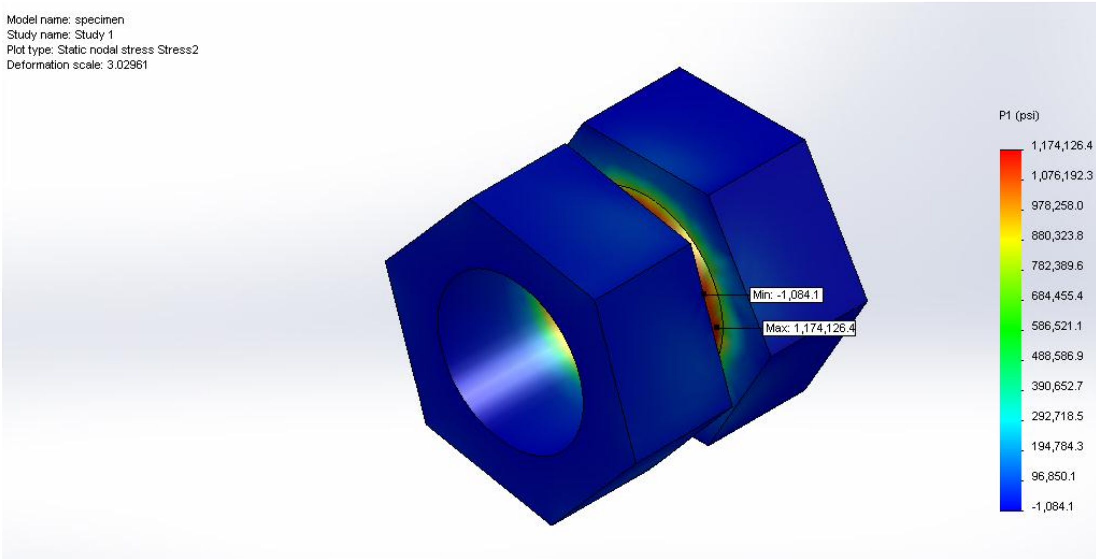


Figure 67 First Principal Stress Study for Specimen

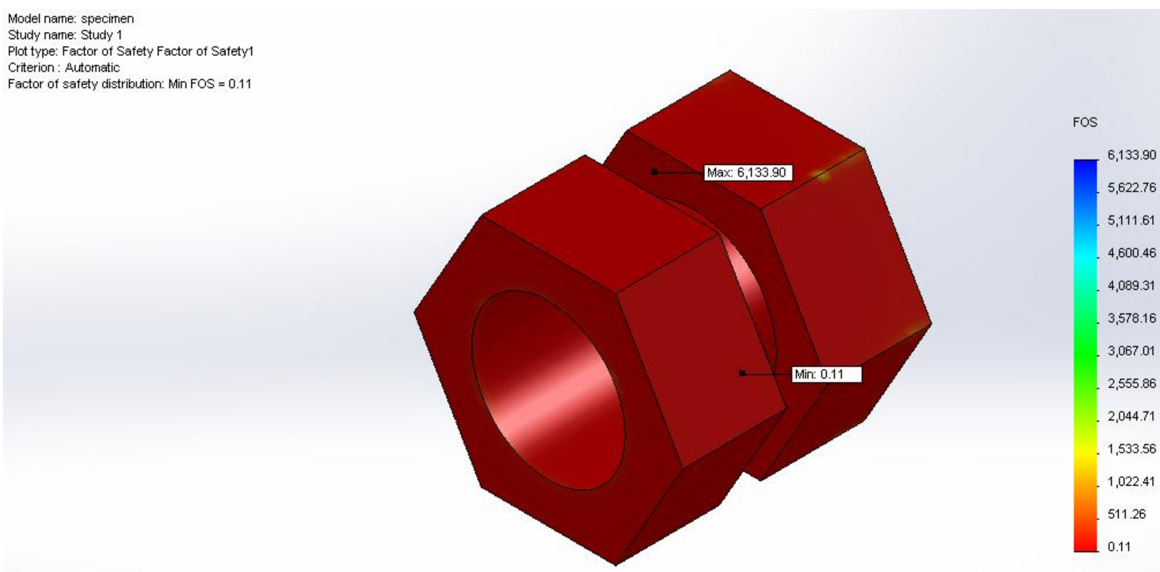


Figure 68 Factor of Safety Study for Specimen

Bar

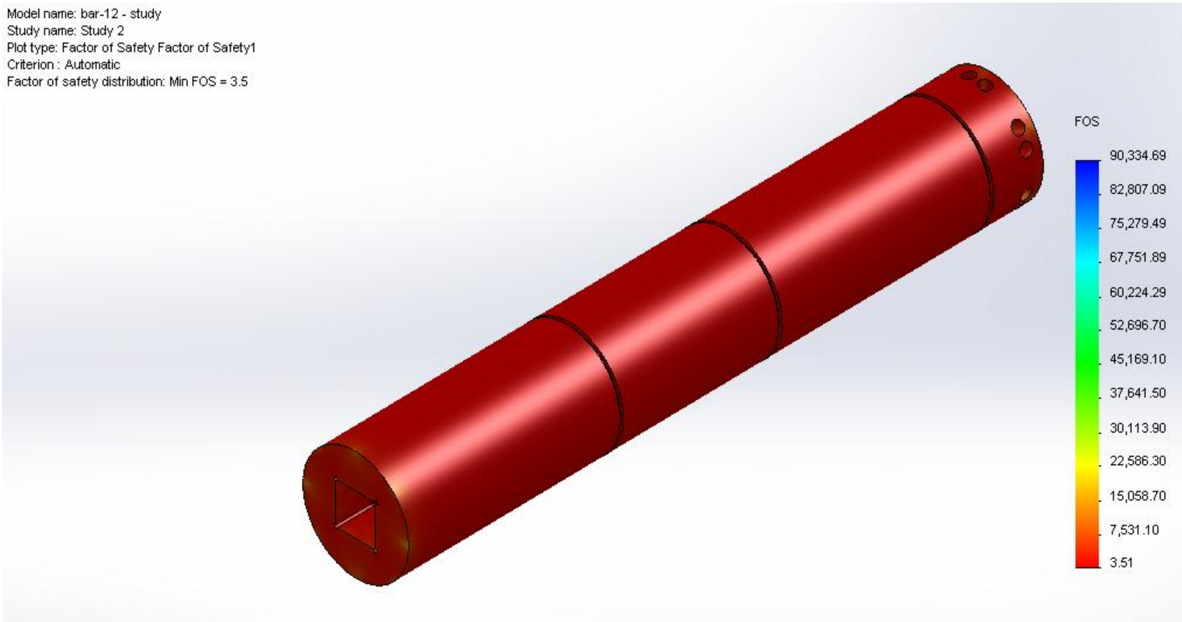


Figure 69 Factor of Safety Study for Bar

Appendix D Raw Data

Time (s)	Voltage (V)	Altered Voltage (V)	Microstrain	Strain Gage	Strain Rate	Specimen Strain	Shear Stress (Pa)
3.86E-01	-1.08	0	0	0	0	0.00E+00	0
3.88E-01	-1.08	0	0	0	0	0.00E+00	0
3.90E-01	-1.08	0	0	0	0	0.00E+00	0
3.92E-01	-1.08	0	0	0	0	0.00E+00	0
3.94E-01	-1.082	-0.002	0.000192771	3.85542E-09	-0.007213605	-1.44E-05	-686.8321018
3.96E-01	-1.08	0	0	0	0	-1.44E-05	0
3.98E-01	-1.08	0	0	0	0	-1.44E-05	0
4.00E-01	-1.082	-0.002	0.000192771	3.85542E-09	-0.007213605	-2.89E-05	-686.8321018
4.02E-01	-1.08	0	0	0	0	-2.89E-05	0
4.04E-01	-1.082	-0.002	0.000192771	3.85542E-09	-0.007213605	-4.33E-05	-686.8321018
4.06E-01	-1.082	-0.002	0.000192771	3.85542E-09	-0.007213605	-5.77E-05	-686.8321018
4.08E-01	-1.082	-0.002	0.000192771	3.85542E-09	-0.007213605	-7.21E-05	-686.8321018
4.10E-01	-1.082	-0.002	0.000192771	3.85542E-09	-0.007213605	-8.66E-05	-686.8321018
4.12E-01	-1.082	-0.002	0.000192771	3.85542E-09	-0.007213605	-1.01E-04	-686.8321018
4.14E-01	-1.082	-0.002	0.000192771	3.85542E-09	-0.007213605	-1.15E-04	-686.8321018
4.16E-01	-1.08	0	0	0	0	-1.15E-04	0
4.18E-01	-1.08	0	0	0	0	-1.15E-04	0
4.20E-01	-1.08	0	0	0	0	-1.15E-04	0
4.22E-01	-1.08	0	0	0	0	-1.15E-04	0
4.24E-01	-1.082	-0.002	0.000192771	3.85542E-09	-0.007213605	-1.30E-04	-686.8321018
4.26E-01	-1.08	0	0	0	0	-1.30E-04	0
4.28E-01	-1.082	-0.002	0.000192771	3.85542E-09	-0.007213605	-1.44E-04	-686.8321018
4.30E-01	-1.082	-0.002	0.000192771	3.85542E-09	-0.007213605	-1.59E-04	-686.8321018
4.32E-01	-1.082	-0.002	0.000192771	3.85542E-09	-0.007213605	-1.73E-04	-686.8321018
4.34E-01	-1.082	-0.002	0.000192771	3.85542E-09	-0.007213605	-1.88E-04	-686.8321018
4.36E-01	-1.082	-0.002	0.000192771	3.85542E-09	-0.007213605	-2.02E-04	-686.8321018
4.38E-01	-1.082	-0.002	0.000192771	3.85542E-09	-0.007213605	-2.16E-04	-686.8321018
4.40E-01	-1.08	0	0	0	0	-2.16E-04	0
4.42E-01	-1.082	-0.002	0.000192771	3.85542E-09	-0.007213605	-2.31E-04	-686.8321018
4.44E-01	-1.082	-0.002	0.000192771	3.85542E-09	-0.007213605	-2.45E-04	-686.8321018
4.46E-01	-1.082	-0.002	0.000192771	3.85542E-09	-0.007213605	-2.60E-04	-686.8321018
4.48E-01	-1.08	0	0	0	0	-2.60E-04	0
4.50E-01	-1.082	-0.002	0.000192771	3.85542E-09	-0.007213605	-2.74E-04	-686.8321018
4.52E-01	-1.08	0	0	0	0	-2.74E-04	0
4.54E-01	-1.08	0	0	0	0	-2.74E-04	0
4.56E-01	-1.08	0	0	0	0	-2.74E-04	0
4.58E-01	-1.082	-0.002	0.000192771	3.85542E-09	-0.007213605	-2.89E-04	-686.8321018
4.60E-01	-1.082	-0.002	0.000192771	3.85542E-09	-0.007213605	-3.03E-04	-686.8321018
4.62E-01	-1.08	0	0	0	0	-3.03E-04	0
4.64E-01	-1.082	-0.002	0.000192771	3.85542E-09	-0.007213605	-3.17E-04	-686.8321018
4.66E-01	-1.08	0	0	0	0	-3.17E-04	0

4.68E-01	-1.08	0	0	0	0	-3.17E-04	0
4.70E-01	-1.078	0.002	-0.000192771	-3.85542E-09	0.007213605	-3.03E-04	686.8321018
4.72E-01	-1.078	0.002	-0.000192771	-3.85542E-09	0.007213605	-2.89E-04	686.8321018
4.74E-01	-1.078	0.002	-0.000192771	-3.85542E-09	0.007213605	-2.74E-04	686.8321018
4.76E-01	-1.078	0.002	-0.000192771	-3.85542E-09	0.007213605	-2.60E-04	686.8321018
4.78E-01	-1.076	0.004	-0.000385542	-7.71084E-09	0.01442721	-2.31E-04	1373.664204
4.80E-01	-1.076	0.004	-0.000385542	-7.71084E-09	0.01442721	-2.02E-04	1373.664204
4.82E-01	-1.074	0.006	-0.000578313	-1.15663E-08	0.021640815	-1.59E-04	2060.496306
4.84E-01	-1.076	0.004	-0.000385542	-7.71084E-09	0.01442721	-1.30E-04	1373.664204
4.86E-01	-1.074	0.006	-0.000578313	-1.15663E-08	0.021640815	-8.66E-05	2060.496306
4.88E-01	-1.074	0.006	-0.000578313	-1.15663E-08	0.021640815	-4.33E-05	2060.496306
4.90E-01	-1.074	0.006	-0.000578313	-1.15663E-08	0.021640815	9.49E-20	2060.496306
4.92E-01	-1.074	0.006	-0.000578313	-1.15663E-08	0.021640815	4.33E-05	2060.496306
4.94E-01	-1.072	0.008	-0.000771084	-1.54217E-08	0.02885442	1.01E-04	2747.328407
4.96E-01	-1.072	0.008	-0.000771084	-1.54217E-08	0.02885442	1.59E-04	2747.328407
4.98E-01	-1.072	0.008	-0.000771084	-1.54217E-08	0.02885442	2.16E-04	2747.328407
5.00E-01	-1.072	0.008	-0.000771084	-1.54217E-08	0.02885442	2.74E-04	2747.328407
5.02E-01	-1.072	0.008	-0.000771084	-1.54217E-08	0.02885442	3.32E-04	2747.328407
5.04E-01	-1.07	0.01	-0.000963855	-1.92771E-08	0.036068026	4.04E-04	3434.160509
5.06E-01	-1.07	0.01	-0.000963855	-1.92771E-08	0.036068026	4.76E-04	3434.160509
5.08E-01	-1.07	0.01	-0.000963855	-1.92771E-08	0.036068026	5.48E-04	3434.160509
5.10E-01	-1.07	0.01	-0.000963855	-1.92771E-08	0.036068026	6.20E-04	3434.160509
5.12E-01	-1.07	0.01	-0.000963855	-1.92771E-08	0.036068026	6.93E-04	3434.160509
5.14E-01	-1.07	0.01	-0.000963855	-1.92771E-08	0.036068026	7.65E-04	3434.160509
5.16E-01	-1.068	0.012	-0.001156627	-2.31325E-08	0.043281631	8.51E-04	4120.992611
5.18E-01	-1.068	0.012	-0.001156627	-2.31325E-08	0.043281631	9.38E-04	4120.992611
5.20E-01	-1.068	0.012	-0.001156627	-2.31325E-08	0.043281631	1.02E-03	4120.992611
5.22E-01	-1.068	0.012	-0.001156627	-2.31325E-08	0.043281631	1.11E-03	4120.992611
5.24E-01	-1.07	0.01	-0.000963855	-1.92771E-08	0.036068026	1.18E-03	3434.160509
5.26E-01	-1.068	0.012	-0.001156627	-2.31325E-08	0.043281631	1.27E-03	4120.992611
5.28E-01	-1.068	0.012	-0.001156627	-2.31325E-08	0.043281631	1.36E-03	4120.992611
5.30E-01	-1.07	0.01	-0.000963855	-1.92771E-08	0.036068026	1.43E-03	3434.160509
5.32E-01	-1.068	0.012	-0.001156627	-2.31325E-08	0.043281631	1.51E-03	4120.992611
5.34E-01	-1.07	0.01	-0.000963855	-1.92771E-08	0.036068026	1.59E-03	3434.160509
5.36E-01	-1.068	0.012	-0.001156627	-2.31325E-08	0.043281631	1.67E-03	4120.992611
5.38E-01	-1.068	0.012	-0.001156627	-2.31325E-08	0.043281631	1.76E-03	4120.992611
5.40E-01	-1.068	0.012	-0.001156627	-2.31325E-08	0.043281631	1.85E-03	4120.992611
5.42E-01	-1.07	0.01	-0.000963855	-1.92771E-08	0.036068026	1.92E-03	3434.160509
5.44E-01	-1.07	0.01	-0.000963855	-1.92771E-08	0.036068026	1.99E-03	3434.160509
5.46E-01	-1.068	0.012	-0.001156627	-2.31325E-08	0.043281631	2.08E-03	4120.992611
5.48E-01	-1.07	0.01	-0.000963855	-1.92771E-08	0.036068026	2.15E-03	3434.160509
5.50E-01	-1.07	0.01	-0.000963855	-1.92771E-08	0.036068026	2.22E-03	3434.160509
5.52E-01	-1.07	0.01	-0.000963855	-1.92771E-08	0.036068026	2.29E-03	3434.160509
5.54E-01	-1.07	0.01	-0.000963855	-1.92771E-08	0.036068026	2.37E-03	3434.160509

5.56E-01	-1.068	0.012	-0.001156627	-2.31325E-08	0.043281631	2.45E-03	4120.992611
5.58E-01	-1.07	0.01	-0.000963855	-1.92771E-08	0.036068026	2.52E-03	3434.160509
5.60E-01	-1.068	0.012	-0.001156627	-2.31325E-08	0.043281631	2.61E-03	4120.992611
5.62E-01	-1.068	0.012	-0.001156627	-2.31325E-08	0.043281631	2.70E-03	4120.992611
5.64E-01	-1.07	0.01	-0.000963855	-1.92771E-08	0.036068026	2.77E-03	3434.160509
5.66E-01	-1.068	0.012	-0.001156627	-2.31325E-08	0.043281631	2.86E-03	4120.992611
5.68E-01	-1.068	0.012	-0.001156627	-2.31325E-08	0.043281631	2.94E-03	4120.992611
5.70E-01	-1.066	0.014	-0.001349398	-2.6988E-08	0.050495236	3.04E-03	4807.824713
5.72E-01	-1.066	0.014	-0.001349398	-2.6988E-08	0.050495236	3.15E-03	4807.824713
5.74E-01	-1.066	0.014	-0.001349398	-2.6988E-08	0.050495236	3.25E-03	4807.824713
5.76E-01	-1.066	0.014	-0.001349398	-2.6988E-08	0.050495236	3.35E-03	4807.824713
5.78E-01	-1.064	0.016	-0.001542169	-3.08434E-08	0.057708841	3.46E-03	5494.656815
5.80E-01	-1.066	0.014	-0.001349398	-2.6988E-08	0.050495236	3.56E-03	4807.824713
5.82E-01	-1.062	0.018	-0.00173494	-3.46988E-08	0.064922446	3.69E-03	6181.488917
5.84E-01	-1.062	0.018	-0.00173494	-3.46988E-08	0.064922446	3.82E-03	6181.488917
5.86E-01	-1.062	0.018	-0.00173494	-3.46988E-08	0.064922446	3.95E-03	6181.488917
5.88E-01	-1.06	0.02	-0.001927711	-3.85542E-08	0.072136051	4.10E-03	6868.321018
5.90E-01	-1.058	0.022	-0.002120482	-4.24096E-08	0.079349656	4.26E-03	7555.15312
5.92E-01	-1.06	0.02	-0.001927711	-3.85542E-08	0.072136051	4.40E-03	6868.321018
5.94E-01	-1.058	0.022	-0.002120482	-4.24096E-08	0.079349656	4.56E-03	7555.15312
5.96E-01	-1.058	0.022	-0.002120482	-4.24096E-08	0.079349656	4.72E-03	7555.15312
5.98E-01	-1.056	0.024	-0.002313253	-4.62651E-08	0.086563261	4.89E-03	8241.985222
6.00E-01	-1.054	0.026	-0.002506024	-5.01205E-08	0.093776867	5.08E-03	8928.817324
6.02E-01	-1.054	0.026	-0.002506024	-5.01205E-08	0.093776867	5.27E-03	8928.817324
6.04E-01	-1.054	0.026	-0.002506024	-5.01205E-08	0.093776867	5.45E-03	8928.817324
6.06E-01	-1.054	0.026	-0.002506024	-5.01205E-08	0.093776867	5.64E-03	8928.817324
6.08E-01	-1.054	0.026	-0.002506024	-5.01205E-08	0.093776867	5.83E-03	8928.817324
6.10E-01	-1.054	0.026	-0.002506024	-5.01205E-08	0.093776867	6.02E-03	8928.817324
6.12E-01	-1.054	0.026	-0.002506024	-5.01205E-08	0.093776867	6.20E-03	8928.817324
6.14E-01	-1.054	0.026	-0.002506024	-5.01205E-08	0.093776867	6.39E-03	8928.817324
6.16E-01	-1.052	0.028	-0.002698795	-5.39759E-08	0.100990472	6.59E-03	9615.649426
6.18E-01	-1.052	0.028	-0.002698795	-5.39759E-08	0.100990472	6.80E-03	9615.649426
6.20E-01	-1.052	0.028	-0.002698795	-5.39759E-08	0.100990472	7.00E-03	9615.649426
6.22E-01	-1.052	0.028	-0.002698795	-5.39759E-08	0.100990472	7.20E-03	9615.649426
6.24E-01	-1.05	0.03	-0.002891566	-5.78313E-08	0.108204077	7.42E-03	10302.48153
6.26E-01	-1.048	0.032	-0.003084337	-6.16867E-08	0.115417682	7.65E-03	10989.31363
6.28E-01	-1.046	0.034	-0.003277108	-6.55422E-08	0.122631287	7.89E-03	11676.14573
6.30E-01	-1.044	0.036	-0.00346988	-6.93976E-08	0.129844892	8.15E-03	12362.97783
6.32E-01	-1.044	0.036	-0.00346988	-6.93976E-08	0.129844892	8.41E-03	12362.97783
6.34E-01	-1.042	0.038	-0.003662651	-7.3253E-08	0.137058497	8.69E-03	13049.80994
6.36E-01	-1.038	0.042	-0.004048193	-8.09639E-08	0.151485708	8.99E-03	14423.47414
6.38E-01	-1.036	0.044	-0.004240964	-8.48193E-08	0.158699313	9.31E-03	15110.30624
6.40E-01	-1.034	0.046	-0.004433735	-8.86747E-08	0.165912918	9.64E-03	15797.13834
6.42E-01	-1.034	0.046	-0.004433735	-8.86747E-08	0.165912918	9.97E-03	15797.13834

6.44E-01	-1.03	0.05	-0.004819277	-9.63855E-08	0.180340128	1.03E-02	17170.80255
6.46E-01	-1.028	0.052	-0.005012048	-1.00241E-07	0.187553733	1.07E-02	17857.63465
6.48E-01	-1.026	0.054	-0.005204819	-1.04096E-07	0.194767338	1.11E-02	18544.46675
6.50E-01	-1.024	0.056	-0.00539759	-1.07952E-07	0.201980943	1.15E-02	19231.29885
6.52E-01	-1.022	0.058	-0.005590361	-1.11807E-07	0.209194549	1.19E-02	19918.13095
6.54E-01	-1.02	0.06	-0.005783133	-1.15663E-07	0.216408154	1.23E-02	20604.96306
6.56E-01	-1.016	0.064	-0.006168675	-1.23373E-07	0.230835364	1.28E-02	21978.62726
6.58E-01	-1.014	0.066	-0.006361446	-1.27229E-07	0.238048969	1.33E-02	22665.45936
6.60E-01	-1.014	0.066	-0.006361446	-1.27229E-07	0.238048969	1.38E-02	22665.45936
6.62E-01	-1.01	0.07	-0.006746988	-1.3494E-07	0.252476179	1.43E-02	24039.12356
6.64E-01	-1.01	0.07	-0.006746988	-1.3494E-07	0.252476179	1.48E-02	24039.12356
6.66E-01	-1.008	0.072	-0.006939759	-1.38795E-07	0.259689784	1.53E-02	24725.95567
6.68E-01	-1.006	0.074	-0.00713253	-1.42651E-07	0.26690339	1.58E-02	25412.78777
6.70E-01	-1.006	0.074	-0.00713253	-1.42651E-07	0.26690339	1.64E-02	25412.78777
6.72E-01	-1.004	0.076	-0.007325301	-1.46506E-07	0.274116995	1.69E-02	26099.61987
6.74E-01	-1.002	0.078	-0.007518072	-1.50361E-07	0.2813306	1.75E-02	26786.45197
6.76E-01	-1.002	0.078	-0.007518072	-1.50361E-07	0.2813306	1.80E-02	26786.45197
6.78E-01	-1.002	0.078	-0.007518072	-1.50361E-07	0.2813306	1.86E-02	26786.45197
6.80E-01	-1	0.08	-0.007710843	-1.54217E-07	0.288544205	1.92E-02	27473.28407
6.82E-01	-1	0.08	-0.007710843	-1.54217E-07	0.288544205	1.98E-02	27473.28407
6.84E-01	-9.98E-01	0.081999974	-0.007903612	-1.58072E-07	0.295757716	2.03E-02	28160.10725
6.86E-01	-9.98E-01	0.081999974	-0.007903612	-1.58072E-07	0.295757716	2.09E-02	28160.10725
6.88E-01	-9.96E-01	0.083999949	-0.008096381	-1.61928E-07	0.302971231	2.15E-02	28846.93076
6.90E-01	-9.96E-01	0.083999949	-0.008096381	-1.61928E-07	0.302971231	2.21E-02	28846.93076
6.92E-01	-9.96E-01	0.083999949	-0.008096381	-1.61928E-07	0.302971231	2.28E-02	28846.93076
6.94E-01	-9.96E-01	0.083999949	-0.008096381	-1.61928E-07	0.302971231	2.34E-02	28846.93076
6.96E-01	-9.94E-01	0.085999982	-0.008289155	-1.65783E-07	0.310184955	2.40E-02	29533.7742
6.98E-01	-9.94E-01	0.085999982	-0.008289155	-1.65783E-07	0.310184955	2.46E-02	29533.7742
7.00E-01	-9.96E-01	0.083999949	-0.008096381	-1.61928E-07	0.302971231	2.52E-02	28846.93076
7.02E-01	-9.94E-01	0.085999982	-0.008289155	-1.65783E-07	0.310184955	2.58E-02	29533.7742
7.04E-01	-9.94E-01	0.085999982	-0.008289155	-1.65783E-07	0.310184955	2.64E-02	29533.7742
7.06E-01	-9.92E-01	0.087999957	-0.008481924	-1.69638E-07	0.31739847	2.71E-02	30220.59771
7.08E-01	-9.90E-01	0.089999931	-0.008674692	-1.73494E-07	0.324611982	2.77E-02	30907.42089
7.10E-01	-9.94E-01	0.085999982	-0.008289155	-1.65783E-07	0.310184955	2.83E-02	29533.7742
7.12E-01	-9.92E-01	0.087999957	-0.008481924	-1.69638E-07	0.31739847	2.90E-02	30220.59771
7.14E-01	-9.94E-01	0.085999982	-0.008289155	-1.65783E-07	0.310184955	2.96E-02	29533.7742
7.16E-01	-9.92E-01	0.087999957	-0.008481924	-1.69638E-07	0.31739847	3.02E-02	30220.59771
7.18E-01	-9.94E-01	0.085999982	-0.008289155	-1.65783E-07	0.310184955	3.09E-02	29533.7742
7.20E-01	-9.92E-01	0.087999957	-0.008481924	-1.69638E-07	0.31739847	3.15E-02	30220.59771
7.22E-01	-9.94E-01	0.085999982	-0.008289155	-1.65783E-07	0.310184955	3.21E-02	29533.7742
7.24E-01	-9.92E-01	0.087999957	-0.008481924	-1.69638E-07	0.31739847	3.27E-02	30220.59771
7.26E-01	-9.90E-01	0.089999931	-0.008674692	-1.73494E-07	0.324611982	3.34E-02	30907.42089
7.28E-01	-9.90E-01	0.089999931	-0.008674692	-1.73494E-07	0.324611982	3.40E-02	30907.42089
7.30E-01	-9.90E-01	0.089999931	-0.008674692	-1.73494E-07	0.324611982	3.47E-02	30907.42089

7.32E-01	-9.90E-01	0.089999931	-0.008674692	-1.73494E-07	0.324611982	3.53E-02	30907.42089
7.34E-01	-9.90E-01	0.089999931	-0.008674692	-1.73494E-07	0.324611982	3.60E-02	30907.42089
7.36E-01	-9.90E-01	0.089999931	-0.008674692	-1.73494E-07	0.324611982	3.66E-02	30907.42089
7.38E-01	-9.90E-01	0.089999931	-0.008674692	-1.73494E-07	0.324611982	3.73E-02	30907.42089
7.40E-01	-9.88E-01	0.091999965	-0.008867467	-1.77349E-07	0.331825709	3.80E-02	31594.26467
7.42E-01	-9.90E-01	0.089999931	-0.008674692	-1.73494E-07	0.324611982	3.86E-02	30907.42089
7.44E-01	-9.88E-01	0.091999965	-0.008867467	-1.77349E-07	0.331825709	3.93E-02	31594.26467
7.46E-01	-9.88E-01	0.091999965	-0.008867467	-1.77349E-07	0.331825709	3.99E-02	31594.26467
7.48E-01	-9.86E-01	0.093999939	-0.009060235	-1.81205E-07	0.339039221	4.06E-02	32281.08784
7.50E-01	-9.88E-01	0.091999965	-0.008867467	-1.77349E-07	0.331825709	4.13E-02	31594.26467
7.52E-01	-9.86E-01	0.093999939	-0.009060235	-1.81205E-07	0.339039221	4.20E-02	32281.08784
7.54E-01	-9.84E-01	0.095999973	-0.009253009	-1.8506E-07	0.346252949	4.26E-02	32967.93162
7.56E-01	-9.84E-01	0.095999973	-0.009253009	-1.8506E-07	0.346252949	4.33E-02	32967.93162
7.58E-01	-9.82E-01	0.097999947	-0.009445778	-1.88916E-07	0.35346646	4.40E-02	33654.75479
7.60E-01	-9.82E-01	0.097999947	-0.009445778	-1.88916E-07	0.35346646	4.48E-02	33654.75479
7.62E-01	-9.80E-01	0.099999981	-0.009638552	-1.92771E-07	0.360680188	4.55E-02	34341.59857
7.64E-01	-9.78E-01	0.101999955	-0.009831321	-1.96626E-07	0.367893699	4.62E-02	35028.42174
7.66E-01	-9.78E-01	0.101999955	-0.009831321	-1.96626E-07	0.367893699	4.69E-02	35028.42174
7.68E-01	-9.76E-01	0.103999929	-0.01002409	-2.00482E-07	0.37510721	4.77E-02	35715.24491
7.70E-01	-9.74E-01	0.105999963	-0.010216864	-2.04337E-07	0.382320938	4.85E-02	36402.08869
7.72E-01	-9.72E-01	0.107999938	-0.010409633	-2.08193E-07	0.389534453	4.92E-02	37088.91221
7.74E-01	-9.72E-01	0.107999938	-0.010409633	-2.08193E-07	0.389534453	5.00E-02	37088.91221
7.76E-01	-9.70E-01	0.109999971	-0.010602407	-2.12048E-07	0.396748177	5.08E-02	37775.75564
7.78E-01	-9.68E-01	0.111999946	-0.010795176	-2.15904E-07	0.403961692	5.16E-02	38462.57916
7.80E-01	-9.66E-01	0.113999979	-0.01098795	-2.19759E-07	0.411175416	5.24E-02	39149.42259
7.82E-01	-9.64E-01	0.115999954	-0.011180718	-2.23614E-07	0.418388931	5.33E-02	39836.24611
7.84E-01	-9.62E-01	0.117999928	-0.011373487	-2.2747E-07	0.425602443	5.41E-02	40523.06928
7.86E-01	-9.60E-01	0.119999962	-0.011566261	-2.31325E-07	0.43281617	5.50E-02	41209.91306
7.88E-01	-9.58E-01	0.121999936	-0.01175903	-2.35181E-07	0.440029682	5.59E-02	41896.73623
7.90E-01	-9.56E-01	0.12399997	-0.011951804	-2.39036E-07	0.447243409	5.68E-02	42583.58001
7.92E-01	-9.54E-01	0.125999944	-0.012144573	-2.42891E-07	0.454456921	5.77E-02	43270.40318
7.94E-01	-9.52E-01	0.127999978	-0.012337347	-2.46747E-07	0.461670649	5.86E-02	43957.24696
7.96E-01	-9.52E-01	0.127999978	-0.012337347	-2.46747E-07	0.461670649	5.95E-02	43957.24696
7.98E-01	-9.52E-01	0.127999978	-0.012337347	-2.46747E-07	0.461670649	6.04E-02	43957.24696
8.00E-01	-9.48E-01	0.131999927	-0.012722885	-2.54458E-07	0.476097675	6.14E-02	45330.89365
8.02E-01	-9.48E-01	0.131999927	-0.012722885	-2.54458E-07	0.476097675	6.24E-02	45330.89365
8.04E-01	-9.46E-01	0.13399996	-0.012915659	-2.58313E-07	0.483311399	6.33E-02	46017.73709
8.06E-01	-9.44E-01	0.135999935	-0.013108427	-2.62169E-07	0.490524914	6.43E-02	46704.5606
8.08E-01	-9.42E-01	0.137999969	-0.013301202	-2.66024E-07	0.497738642	6.53E-02	47391.40438
8.10E-01	-9.40E-01	0.139999943	-0.01349397	-2.69879E-07	0.504952153	6.63E-02	48078.22755
8.12E-01	-9.42E-01	0.137999969	-0.013301202	-2.66024E-07	0.497738642	6.73E-02	47391.40438
8.14E-01	-9.42E-01	0.137999969	-0.013301202	-2.66024E-07	0.497738642	6.83E-02	47391.40438
8.16E-01	-9.38E-01	0.141999977	-0.013686745	-2.73735E-07	0.512165881	6.93E-02	48765.07133
8.18E-01	-9.38E-01	0.141999977	-0.013686745	-2.73735E-07	0.512165881	7.03E-02	48765.07133

8.20E-01	-9.38E-01	0.141999977	-0.013686745	-2.73735E-07	0.512165881	7.14E-02	48765.07133
8.22E-01	-9.38E-01	0.141999977	-0.013686745	-2.73735E-07	0.512165881	7.24E-02	48765.07133
8.24E-01	-9.36E-01	0.143999951	-0.013879513	-2.7759E-07	0.519379392	7.34E-02	49451.89451
8.26E-01	-9.36E-01	0.143999951	-0.013879513	-2.7759E-07	0.519379392	7.45E-02	49451.89451
8.28E-01	-9.36E-01	0.143999951	-0.013879513	-2.7759E-07	0.519379392	7.55E-02	49451.89451
8.30E-01	-9.34E-01	0.145999985	-0.014072288	-2.81446E-07	0.52659312	7.66E-02	50138.73828
8.32E-01	-9.34E-01	0.145999985	-0.014072288	-2.81446E-07	0.52659312	7.76E-02	50138.73828
8.34E-01	-9.34E-01	0.145999985	-0.014072288	-2.81446E-07	0.52659312	7.87E-02	50138.73828
8.36E-01	-9.34E-01	0.145999985	-0.014072288	-2.81446E-07	0.52659312	7.97E-02	50138.73828
8.38E-01	-9.34E-01	0.145999985	-0.014072288	-2.81446E-07	0.52659312	8.08E-02	50138.73828
8.40E-01	-9.34E-01	0.145999985	-0.014072288	-2.81446E-07	0.52659312	8.18E-02	50138.73828
8.42E-01	-9.34E-01	0.145999985	-0.014072288	-2.81446E-07	0.52659312	8.29E-02	50138.73828
8.44E-01	-9.32E-01	0.147999959	-0.014265056	-2.85301E-07	0.533806631	8.40E-02	50825.56146
8.46E-01	-9.34E-01	0.145999985	-0.014072288	-2.81446E-07	0.52659312	8.50E-02	50138.73828
8.48E-01	-9.34E-01	0.145999985	-0.014072288	-2.81446E-07	0.52659312	8.61E-02	50138.73828
8.50E-01	-9.32E-01	0.147999959	-0.014265056	-2.85301E-07	0.533806631	8.71E-02	50825.56146
8.52E-01	-9.34E-01	0.145999985	-0.014072288	-2.81446E-07	0.52659312	8.82E-02	50138.73828
8.54E-01	-9.34E-01	0.145999985	-0.014072288	-2.81446E-07	0.52659312	8.92E-02	50138.73828
8.56E-01	-9.34E-01	0.145999985	-0.014072288	-2.81446E-07	0.52659312	9.03E-02	50138.73828
8.58E-01	-9.32E-01	0.147999959	-0.014265056	-2.85301E-07	0.533806631	9.14E-02	50825.56146
8.60E-01	-9.34E-01	0.145999985	-0.014072288	-2.81446E-07	0.52659312	9.24E-02	50138.73828
8.62E-01	-9.34E-01	0.145999985	-0.014072288	-2.81446E-07	0.52659312	9.35E-02	50138.73828
8.64E-01	-9.34E-01	0.145999985	-0.014072288	-2.81446E-07	0.52659312	9.45E-02	50138.73828
8.66E-01	-9.34E-01	0.145999985	-0.014072288	-2.81446E-07	0.52659312	9.56E-02	50138.73828
8.68E-01	-9.34E-01	0.145999985	-0.014072288	-2.81446E-07	0.52659312	9.66E-02	50138.73828
8.70E-01	-9.36E-01	0.143999951	-0.013879513	-2.7759E-07	0.519379392	9.77E-02	49451.89451
8.72E-01	-9.36E-01	0.143999951	-0.013879513	-2.7759E-07	0.519379392	9.87E-02	49451.89451
8.74E-01	-9.34E-01	0.145999985	-0.014072288	-2.81446E-07	0.52659312	9.97E-02	50138.73828
8.76E-01	-9.34E-01	0.145999985	-0.014072288	-2.81446E-07	0.52659312	1.01E-01	50138.73828
8.78E-01	-9.34E-01	0.145999985	-0.014072288	-2.81446E-07	0.52659312	1.02E-01	50138.73828
8.80E-01	-9.34E-01	0.145999985	-0.014072288	-2.81446E-07	0.52659312	1.03E-01	50138.73828
8.82E-01	-9.36E-01	0.143999951	-0.013879513	-2.7759E-07	0.519379392	1.04E-01	49451.89451
8.84E-01	-9.36E-01	0.143999951	-0.013879513	-2.7759E-07	0.519379392	1.05E-01	49451.89451
8.86E-01	-9.36E-01	0.143999951	-0.013879513	-2.7759E-07	0.519379392	1.06E-01	49451.89451
8.88E-01	-9.34E-01	0.145999985	-0.014072288	-2.81446E-07	0.52659312	1.07E-01	50138.73828
8.90E-01	-9.36E-01	0.143999951	-0.013879513	-2.7759E-07	0.519379392	1.08E-01	49451.89451
8.92E-01	-9.36E-01	0.143999951	-0.013879513	-2.7759E-07	0.519379392	1.09E-01	49451.89451
8.94E-01	-9.38E-01	0.141999977	-0.013686745	-2.73735E-07	0.512165881	1.10E-01	48765.07133
8.96E-01	-9.38E-01	0.141999977	-0.013686745	-2.73735E-07	0.512165881	1.11E-01	48765.07133
8.98E-01	-9.38E-01	0.141999977	-0.013686745	-2.73735E-07	0.512165881	1.12E-01	48765.07133
9.00E-01	-9.52E-01	0.127999978	-0.012337347	-2.46747E-07	0.461670649	1.13E-01	43957.24696
9.02E-01	-9.72E-01	0.107999938	-0.010409633	-2.08193E-07	0.389534453	1.14E-01	37088.91221
9.04E-01	-9.88E-01	0.091999965	-0.008867467	-1.77349E-07	0.331825709	1.15E-01	31594.26467
9.06E-01	-1	0.08	-0.007710843	-1.54217E-07	0.288544205	1.15E-01	27473.28407

9.08E-01	-1.008	0.072	-0.006939759	-1.38795E-07	0.259689784	1.16E-01	24725.95567
9.10E-01	-1.018	0.062	-0.005975904	-1.19518E-07	0.223621759	1.16E-01	21291.79516
9.12E-01	-1.024	0.056	-0.00539759	-1.07952E-07	0.201980943	1.17E-01	19231.29885
9.14E-01	-1.028	0.052	-0.005012048	-1.00241E-07	0.187553733	1.17E-01	17857.63465
9.16E-01	-1.034	0.046	-0.004433735	-8.86747E-08	0.165912918	1.17E-01	15797.13834
9.18E-01	-1.04	0.04	-0.003855422	-7.71084E-08	0.144272102	1.18E-01	13736.64204
9.20E-01	-1.046	0.034	-0.003277108	-6.55422E-08	0.122631287	1.18E-01	11676.14573
9.22E-01	-1.052	0.028	-0.002698795	-5.39759E-08	0.100990472	1.18E-01	9615.649426
9.24E-01	-1.058	0.022	-0.002120482	-4.24096E-08	0.079349656	1.18E-01	7555.15312
9.26E-01	-1.062	0.018	-0.00173494	-3.46988E-08	0.064922446	1.18E-01	6181.488917
9.28E-01	-1.066	0.014	-0.001349398	-2.6988E-08	0.050495236	1.18E-01	4807.824713
9.30E-01	-1.068	0.012	-0.001156627	-2.31325E-08	0.043281631	1.18E-01	4120.992611
9.32E-01	-1.072	0.008	-0.000771084	-1.54217E-08	0.02885442	1.19E-01	2747.328407
9.34E-01	-1.074	0.006	-0.000578313	-1.15663E-08	0.021640815	1.19E-01	2060.496306
9.36E-01	-1.076	0.004	-0.000385542	-7.71084E-09	0.01442721	1.19E-01	1373.664204
9.38E-01	-1.076	0.004	-0.000385542	-7.71084E-09	0.01442721	1.19E-01	1373.664204
9.40E-01	-1.076	0.004	-0.000385542	-7.71084E-09	0.01442721	1.19E-01	1373.664204
9.42E-01	-1.08	0	0	0	0	1.19E-01	0
9.44E-01	-1.078	0.002	-0.000192771	-3.85542E-09	0.007213605	1.19E-01	686.8321018
9.46E-01	-1.08	0	0	0	0	1.19E-01	0
9.48E-01	-1.08	0	0	0	0	1.19E-01	0
9.50E-01	-1.08	0	0	0	0	1.19E-01	0
9.52E-01	-1.08	0	0	0	0	1.19E-01	0
9.54E-01	-1.08	0	0	0	0	1.19E-01	0
9.56E-01	-1.082	-0.002	0.000192771	3.85542E-09	-0.007213605	1.19E-01	-686.8321018
9.58E-01	-1.082	-0.002	0.000192771	3.85542E-09	-0.007213605	1.19E-01	-686.8321018
9.60E-01	-1.08	0	0	0	0	1.19E-01	0
9.62E-01	-1.08	0	0	0	0	1.19E-01	0
9.64E-01	-1.082	-0.002	0.000192771	3.85542E-09	-0.007213605	1.19E-01	-686.8321018
9.66E-01	-1.082	-0.002	0.000192771	3.85542E-09	-0.007213605	1.19E-01	-686.8321018
9.68E-01	-1.082	-0.002	0.000192771	3.85542E-09	-0.007213605	1.19E-01	-686.8321018
9.70E-01	-1.082	-0.002	0.000192771	3.85542E-09	-0.007213605	1.19E-01	-686.8321018
9.72E-01	-1.082	-0.002	0.000192771	3.85542E-09	-0.007213605	1.19E-01	-686.8321018
9.74E-01	-1.082	-0.002	0.000192771	3.85542E-09	-0.007213605	1.19E-01	-686.8321018
9.76E-01	-1.082	-0.002	0.000192771	3.85542E-09	-0.007213605	1.19E-01	-686.8321018
9.78E-01	-1.082	-0.002	0.000192771	3.85542E-09	-0.007213605	1.19E-01	-686.8321018
9.80E-01	-1.082	-0.002	0.000192771	3.85542E-09	-0.007213605	1.19E-01	-686.8321018
9.82E-01	-1.082	-0.002	0.000192771	3.85542E-09	-0.007213605	1.18E-01	-686.8321018
9.84E-01	-1.082	-0.002	0.000192771	3.85542E-09	-0.007213605	1.18E-01	-686.8321018
9.86E-01	-1.082	-0.002	0.000192771	3.85542E-09	-0.007213605	1.18E-01	-686.8321018
9.88E-01	-1.082	-0.002	0.000192771	3.85542E-09	-0.007213605	1.18E-01	-686.8321018
9.90E-01	-1.082	-0.002	0.000192771	3.85542E-09	-0.007213605	1.18E-01	-686.8321018
9.92E-01	-1.082	-0.002	0.000192771	3.85542E-09	-0.007213605	1.18E-01	-686.8321018
9.94E-01	-1.082	-0.002	0.000192771	3.85542E-09	-0.007213605	1.18E-01	-686.8321018

9.96E-01	-1.084	-0.004	0.000385542	7.71084E-09	-0.01442721	1.18E-01	-1373.664204
9.98E-01	-1.082	-0.002	0.000192771	3.85542E-09	-0.007213605	1.18E-01	-686.8321018
1	-1.082	-0.002	0.000192771	3.85542E-09	-0.007213605	1.18E-01	-686.8321018
1.002	-1.082	-0.002	0.000192771	3.85542E-09	-0.007213605	1.18E-01	-686.8321018
1.004	-1.082	-0.002	0.000192771	3.85542E-09	-0.007213605	1.18E-01	-686.8321018
1.006	-1.082	-0.002	0.000192771	3.85542E-09	-0.007213605	1.18E-01	-686.8321018
1.008	-1.082	-0.002	0.000192771	3.85542E-09	-0.007213605	1.18E-01	-686.8321018
1.01	-1.082	-0.002	0.000192771	3.85542E-09	-0.007213605	1.18E-01	-686.8321018
1.012	-1.082	-0.002	0.000192771	3.85542E-09	-0.007213605	1.18E-01	-686.8321018
1.014	-1.08	0	0	0	0	1.18E-01	0
1.016	-1.082	-0.002	0.000192771	3.85542E-09	-0.007213605	1.18E-01	-686.8321018
1.018	-1.082	-0.002	0.000192771	3.85542E-09	-0.007213605	1.18E-01	-686.8321018
1.02	-1.082	-0.002	0.000192771	3.85542E-09	-0.007213605	1.18E-01	-686.8321018
1.022	-1.082	-0.002	0.000192771	3.85542E-09	-0.007213605	1.18E-01	-686.8321018
1.024	-1.082	-0.002	0.000192771	3.85542E-09	-0.007213605	1.18E-01	-686.8321018
1.026	-1.082	-0.002	0.000192771	3.85542E-09	-0.007213605	1.18E-01	-686.8321018
1.028	-1.082	-0.002	0.000192771	3.85542E-09	-0.007213605	1.18E-01	-686.8321018
1.03	-1.08	0	0	0	0	1.18E-01	0
1.032	-1.082	-0.002	0.000192771	3.85542E-09	-0.007213605	1.18E-01	-686.8321018
1.034	-1.082	-0.002	0.000192771	3.85542E-09	-0.007213605	1.18E-01	-686.8321018
1.036	-1.08	0	0	0	0	1.18E-01	0

Appendix E Manufacturing Quote and Proposal

FLORIDA INTERNATIONAL UNIVERSITY

Engineering Manufacturing Center

PROPOSAL

CUSTOMER:_Jonathan Gomez PID_ Dept:_MME_

Contact # 786-553-7312 Email jgome074@fiu.edu

PROPOSAL: MME-022312 DATE: 02-23-2012

REF. Torsional Bar components

Project Scope:
Machine from customer supplied material and drawings (1" dia x 6" long 6061 Al), 1-set (2 pieces) 12 holes configuration and one set (2 pieces) 6 hole configuration sample holding shafts. ALSO modify steel plate provided by the EMC by adding 8- threaded holes ¼-20 to allow clearance in bearing block holes which are .312"

Est. Labor costs_$195. 00 Est. Material/Tooling costs: 15.00 TOTAL COST: _$210.00

Estimated Completion Time : 1-week
(Work begins when signed agreement form and ID Transfer is returned and materials have been received)

If you agree to the above proposal, please sign below. Also an ID Transfer must be completed using information on page 2. Fax a copy of both the Proposal and ID Transfer and mail originals to the address below. Once a completed faxed copy and materials have been received we will begin work.

I approve and accept this proposal for the above named Student, Faculty or Staff
(Note: Must be signed by an ID Transfer approving authority)

Sign ________ *Date* 2/27/12 *Print Name* DR. SABRI TOSUNOGLU

Terms:
Changes to the design after estimate is given will have to be evaluated and could result in additional costs. Above is only an estimate and actual labor costs could be more or less depending on actual build times. If final cost will be above estimate given, you will be contacted prior to completion of the project in order to give your approval of any additional costs and another ID Transfer must be issued.

1

FIU-Engineering Manufacturing Center (Rm: OU-118) - 10555 W. Flagler Street - Mail Stop EC 3475 - Miami, FL 33174
Phone: 305-348-6557 Fax: 305-348-6557

Appendix F Calibration Information

ARMSTRONG
INDUSTRIAL HAND TOOLS

CERTIFICATE OF CALIBRATION

TORQUE INSTRUMENT SPECIFICATIONS

MODEL CG2100FQC-ARBH SERIAL NUMBER 5110960682 CONDITION NEW

CALIBRATION SPECIFICATION	ASME B107.14-2004		ISO 6789-2003
TYPE	2	TYPE	2
CLASS	A	CLASS	A
STYLE	2	TEST TEMPERATURE	20 +/- 5 DEG. C.
DESIGN	B	TEST HUMIDITY	< 50 %
LOADING METHOD	MECHANICAL	GRAVITY POSITION	NEUTRAL
REQUIRED ACCURACY	+/- 3% CW		

CALIBRATION TEST RESULTS

NOMINAL	UNITS	ACTUAL	CW % ERROR
20	FT-LBS	20.31	1.57
60	FT-LBS	59.05	-1.58
100	FT-LBS	101.56	1.56

Apex Tool Group certifies that the calibration of this torque instrument has been tested with the equipment listed below and that the test equipment is calibrated with standards traceable to the NATIONAL INSTITUTE of STANDARDS and TECHNOLOGY (NIST) in compliance with ANSI/NCSL Z540-I & ISO/IEC 17025. Total measurement system uncertainty is less than 50% of the stated product accuracy

TEST EQUIPMENT AND STANDARDS

TORQUE CERTIFICATION CELL:	6	TORQUE SYSTEM CALIBRATION DATE:	12/10/2011
TORQUE TESTER SERIAL NO.:	1111	TORQUE TRANSDUCER SERIAL NO.:	800
WEIGHT SET ID:	Troemner class "F"	MOMENT ARM SERIAL NO.:	JS01001
WEIGHT CERTIFICATION:	822/266426-02	MOMENT ARM CERTIFICATION:	821/273515-06
CERTIFICATION DATE:	7/26/2011	CERTIFICATION DATE:	7/26/2011

WRENCH CERTIFIED AT: APEX TOOL GROUP
3000 West Kingsley Road
Garland, Texas

TESTED BY: Hoa
TEST DATE: 1/10/2012

NOTICE: This record supercedes any generic or previously dated certifications and shall not be reproduced except in full

FEATURES

- Limits torque applied with reduced-friction release mechanism.
- Can be used with confidence in all automotive, aircraft, marine and industrial applications.
- Operates and ratchets in both right and left hand directions. May be used for uncontrolled wrenching as long as torque does not exceed maximum capacity.
- Lock ring prevents accidental change of torque setting.
- Durable aluminum handle features an easy to grip diamond knurl surface and scratch resistant anodized coating.
- Ratchet action requires only 10 degrees handle travel.
- May be used continually at maximum torque capacity.
- Mechanism protected from routine contamination.
- Finished with tough, durable chromium-nickel plating.
- Wrench made of highest quality heat-treated steel.

SUGGESTIONS

Proper use of this professional torque wrench will give you complete satisfaction in its performance and reliability. Following are some helpful tips:

1. Greater torque accuracy is assured by gripping it properly. Grasp the GRIP, not the SHAFT, and pull smoothly.
2. Each torque wrench is lubricated before leaving the factory. If it has not been used for some time, it should be operated several times to re-distribute the lubricant within the working mechanism.
3. Never attempt to turn the GRIP when the LOCK RING is in the "LOCK" position.
4. Never set for higher or lower torque values than those indicated on your wrench.
5. For greater accuracy, clean all thread surfaces and remove any burrs on the fasteners being used.
6. **WARNING**-never use your torque wrench to apply more torque that its rated capacity.
7. It is not necessary to return this wrench to its lowest calibrated value after use unless it is to be stored for an extended period of time.

DO NOT OVERTORQUE

CERTIFICATION

This torque wrench is certified to have been calibrated prior to shipment to accuracy of +/- 3% in the clockwise direction on readings from 20% to 100% of capacity. On readings below 20% of capacity, the accuracy is +/- one scale increment

REPAIR AND CALIBRATION SERVICE

Periodically, all torque wrenches should be checked for accuracy. *An out of calibration torque wrench can cause part or tool breakage. Recalibration* should be done at least once a year, or every 5000 torque application cycles, whichever comes first. Recalibration is also recommended after any abnormal handling.

WARRANTY

Armstrong Torque Products are warranted to (1) be free of defects in material and workmanship, and (2) meet out of the box calibration accuracy standards as stated in the product literature. Accuracy standards for calibration are warranted for 90 days from date of purchase. Products for which Warranty Repair is requested should be returned, at Buyer's cost, for evaluation to:

Angle Repair & Calibration Service, Inc.
175 Angle Drive
Beckley, West Virginia 25801
(304) 253-5729

Armstrong Torque Products are precision instruments that contain moving parts. These components are subject to normal wear through use and replacement thereof is the responsibility of Buyer. Torque Products should be routinely checked for calibration at an Authorized Repair Center using Armstrong repair parts.

This Warranty shall not apply to Products which have been misused, abused, damaged by accident or otherwise, repaired by anyone other than an Authorized Repair Center or modified by anyone other than Apex Tool Group and is in lieu of all other warranties, whether expressed, implied, or statutory. THE IMPLIED WARRANTIES OF MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE ARE SPECIFICALLY EXCLUDED. Buyer's sole and exclusive remedy for breach of this Warranty is at the option of Danaher Tool Group, repair or replacement of the defective Product. IN NO EVENT WILL APEX TOOL GROUP BE LIABLE FOR ANY INDIRECT SPECIAL, INCIDENTAL, CONSEQUENTIAL, OR PUNITIVE DAMAGES ARISING FROM BREACH OF THIS WARRANTY, EVEN IF APEX TOOL GROUP HAS BEEN ADVISED OF THE POSSIBILITY OF SUCH DAMAGES.

For further information on Armstrong Torque Products or Authorized Repair Centers, please contact us at
APEX Tool Group
Armstrong Industrial Hand Tools
(800) 866-5753

All Armstrong Dial Indicating Torque Wrenches comply with both American Standard ANSI/ASME B107.14M, and International Standard ISO 6789

REVISED/PRINTED IN USA 06-06 FORM 600AR-90

MICROMETER ADJUSTABLE TORQUE WRENCH

ARMSTRONG®
INDUSTRIAL HAND TOOLS

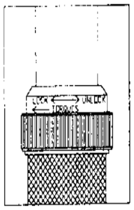
MADE IN U.S.A.

OPERATING INSTRUCTIONS

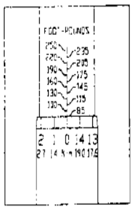
APEX Tool Group
14600 York Road
Suite A
Sparks, MD 21152
Phone: (800) 688-8949
Fax: (410) 472-2057

ADJUSTING YOUR MICROMETER TORQUE WRENCH

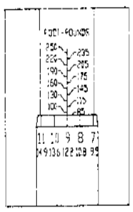
CAUTION-Do not turn GRIP with the LOCK RING in the lock position. Damage to the adjusting mechanism may occur.



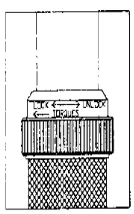
1. To UNLOCK, hold Handle GRIP with one hand and turn the LOCK RING clockwise until it stops.



2. Rotate GRIP until "0" on the THIMBLE SCALE reaches the primary number of the desired torque value on the SHAFT MAIN SCALE.



3. Continue rotating the GRIP if the desired torque value is between the primary numbers on the MAIN SCALE. Add the secondary number on the THIMBLE SCALE to the primary number on the MAIN SCALE to achieve the desired torque value.

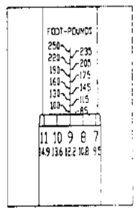


4. To lock wrench, hold handle GRIP with one hand and turn the LOCK RING counterclockwise until it stops.

EXAMPLES OF TORQUE SETTINGS

NOTE: Many models have both American Standard and Metric Scales on the same wrench.

The Main Scale American Standard graduations are on the front of the SHAFT and the Thimble Scale graduations are closest to the beveled edge. The Main Scale Metric graduations are on the reverse side of the shaft and the Thimble Scale Metric graduations are below the American Standard graduations.

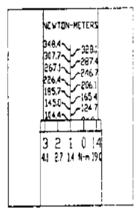


EXAMPLE - STANDARD

For a torque setting of 94 foot pounds, rotate GRIP until the "0" on the THIMBLE SCALE is aligned with the "85" on the "FT.LB." MAIN SCALE.

Continue rotating GRIP clockwise until the "9" on the THIMBLE SCALE is aligned with the center line on the "FT.LB." MAIN SCALE. The wrench is now set at 94 foot pounds.

Put the LOCK RING in the lock position before using.



EXAMPLE - METRIC

For a torque setting of 105.8 Newton meters, rotate GRIP until the "0" on the THIMBLE SCALE is aligned with the "104.4" on the "N.m" MAIN SCALE.

Continue rotating GRIP clockwise until the "1.4" on the Metric THIMBLE SCALE is aligned with the center line of the "N.m." MAIN SCALE.

The wrench is now set at 105.8 N.m (104.4 + 1.4 = 105.8). Put the LOCK RING in the lock position before using.

HOW TO APPLY TORQUE

1. This Micrometer Adjustable Torque Wrench is designed so that when force is properly applied to the handgrip, an audible signal and/or impulse feel will indicate that the desired torque has been attained. DO NOT pull beyond this point.

CAUTION: The audible signal/or impulse feel is an indicator that the proper torque has been attained. Over torquing beyond these signals could cause fastener failure.

Additionally, when wrench is set at low end of the torque range, the degree of signal and impulse will be less than when set at the high end of the range. Therefore, care must be taken at low end of scale to hear signal or feel impulse.

2. To properly apply torque, attach socket securely on torque wrench square drive and position socket on fastener so that tilting will not occur. Grasp the center of hand grip and apply a slow steadily increasing force perpendicular (90 degrees) to the torque wench body and perpendicular (90 degrees) to the center line of the square drive, socket, and fastener.

3. Turn the fastener down with a smooth and even force applied to the handle of the torque wrench. As turning resistance increases pull more slowly. To assure accuracy, the fastener must be in motion when the torque measurement is made.

WARNING: Any change from the above procedure will result in a change of torque being applied. This includes standard torque wrenches, flex head torque wrenches, universal joints, and universal sockets. DO NOT USE universal joints or universal sockets due to the complexity of determining the associated error. If you need angular access, use a flex head torque wrench and compute the associated error as indicated below.

FLEX TORQUE WRENCHES

To compute the torque being applied by a flex head torque wrench:

Torque applied = Cosine (Angle of flex) x Wrench setting

Wrench setting = (Torque required)/Cosine (Angle of flex)

I.E. With head flexed 20° and required torque = 100 ft-lbs,

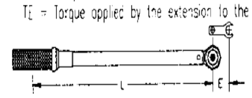
Wrench setting = 100 ft-lbs/Cosine 20° = 106.4 ft-lbs

EXTENSIONS

When it is necessary to use an extension that changes the effective lever length of the torque wrench, torque being applied will change. Compute adjustments as follows:

TW = Torque set on wrench

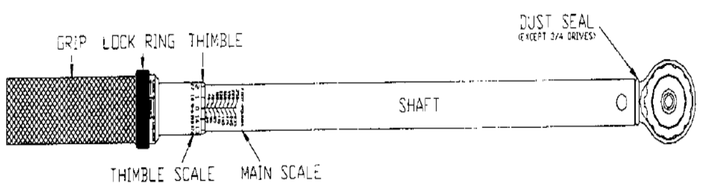
TE = Torque applied by the extension to the fastener



$TW = (TE \times L) / (L + E)$

$TE = (TW \times (L + E)) / L$

NOTICE: Socket extension bars that are axially in line with the square drive do not cause error and need no adjustment.



Appendix G: Stress vs. Strain Diagrams for Transmitter Bar

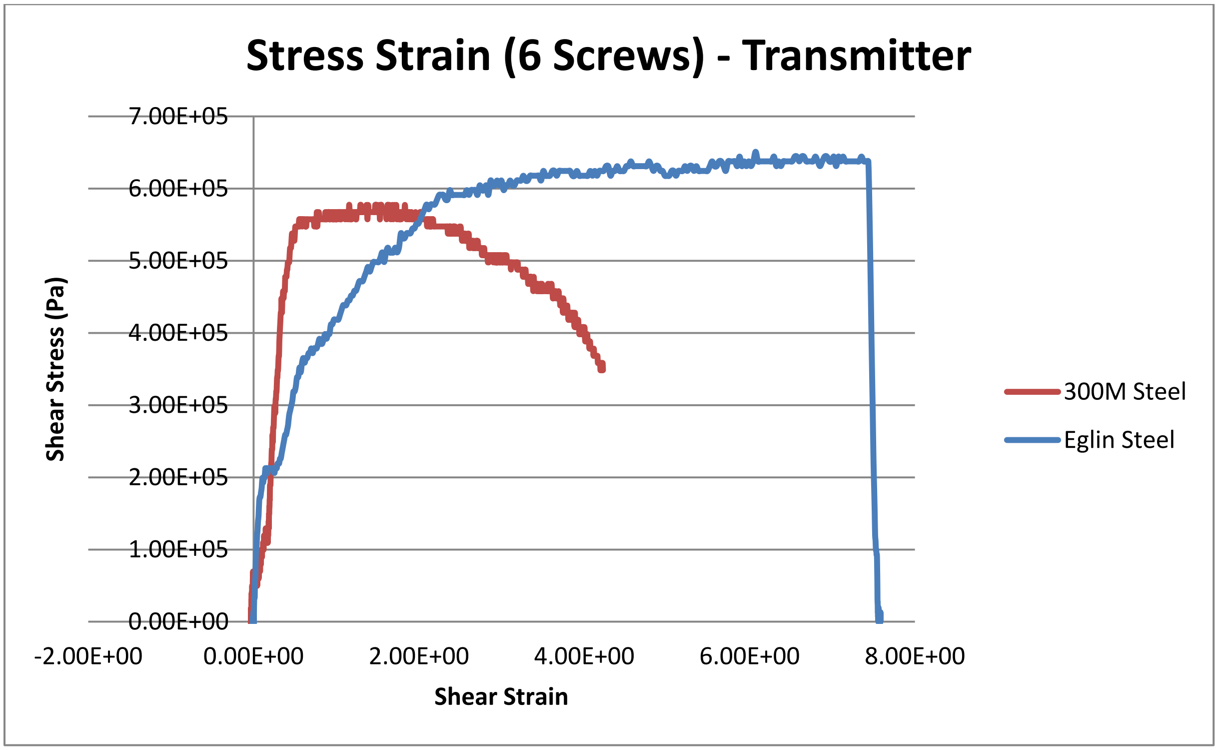


Figure 70 Shear Stress and Strain Diagram for 6 Set Screws-Transmitter

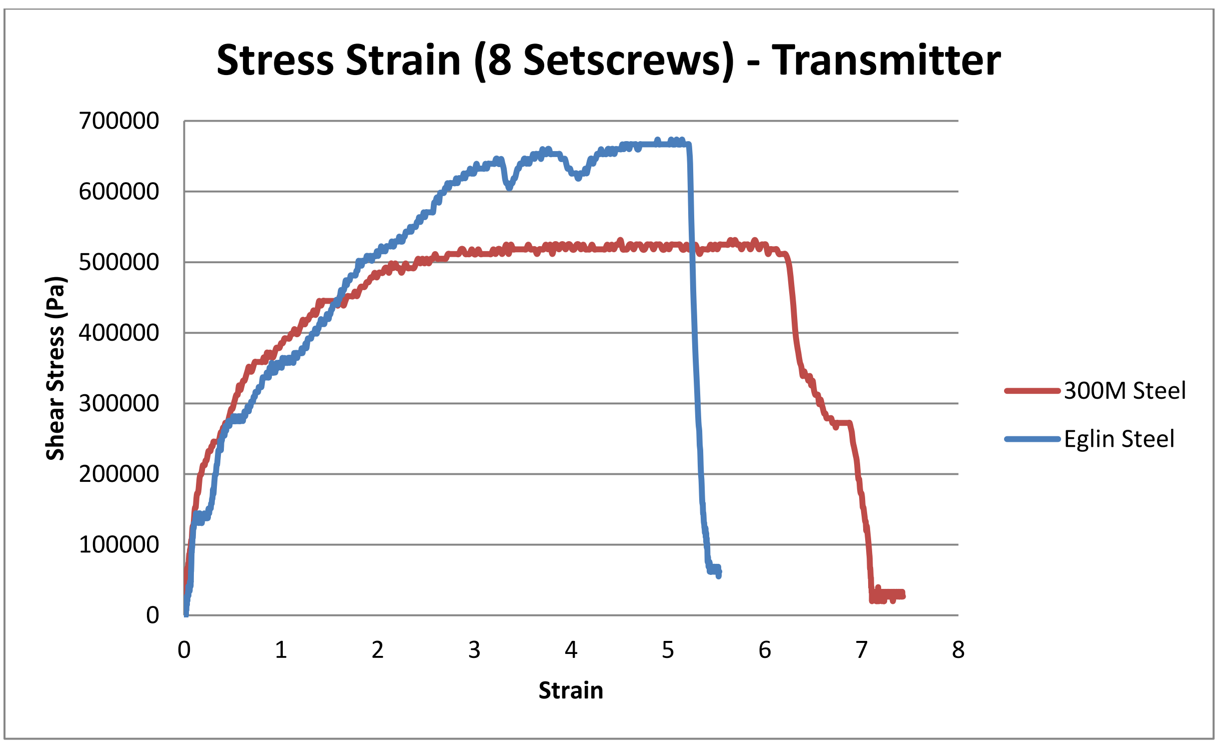


Figure 71 Shear Stress and Strain Diagram for 8 Set Screws-Transmitter

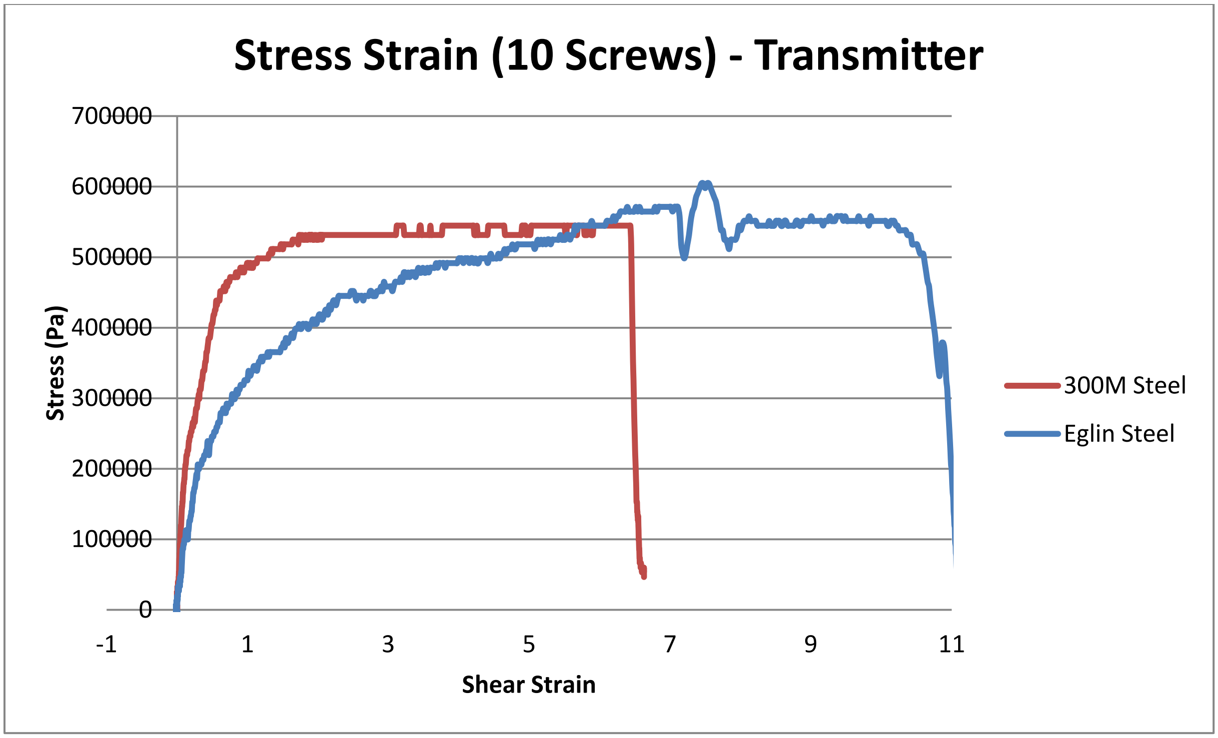


Figure 72 Shear Stress and Strain Diagram for 10 Set Screws-Transmitter

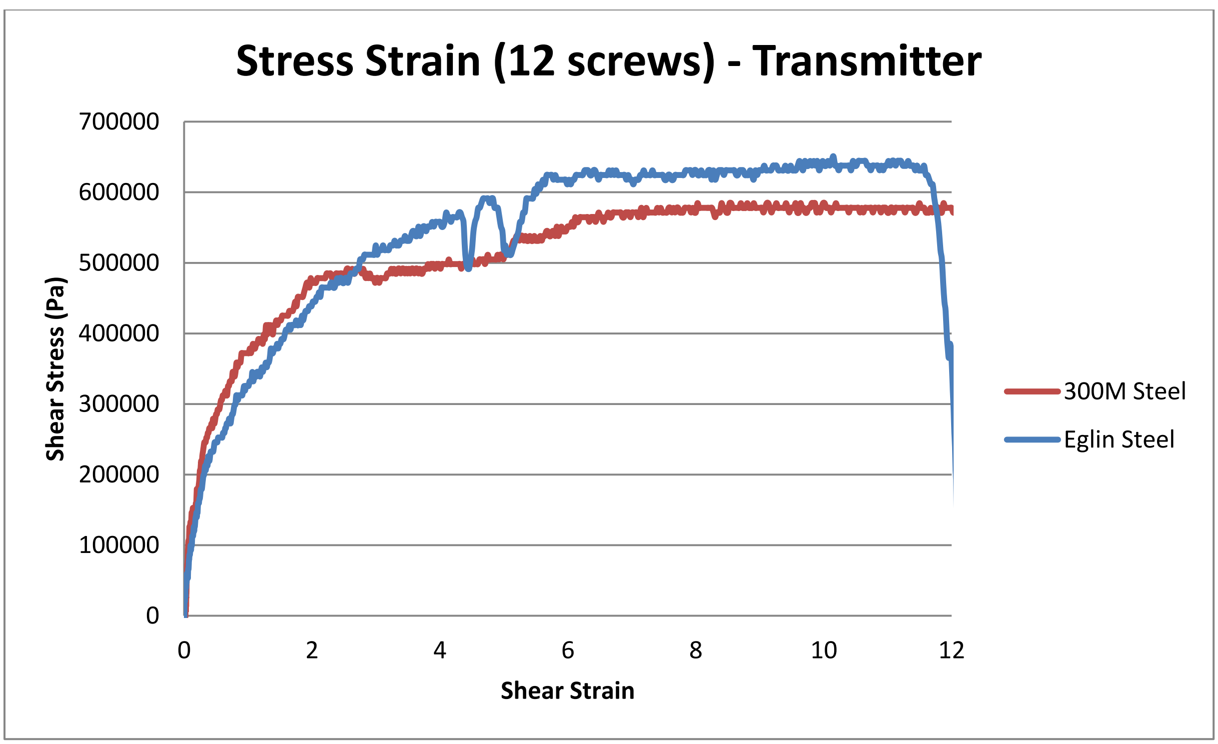


Figure 73 Shear Stress and Strain Diagram for 12 Set Screws-Transmitter

Appendix H: Apparatus

Figure 74 Oscilloscope TDS 2024B